

Digital Innovations in Architecture,
Engineering and Construction

Bárbara Rangel
Ana Sofia Guimarães
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Leonardo Santana *Editors*

3D Printing for Construction with Alternative Materials

 Springer

Digital Innovations in Architecture, Engineering and Construction

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The Architecture, Engineering and Construction (AEC) industry is experiencing an unprecedented transformation from conventional labor-intensive activities to automation using innovative digital technologies and processes. This new paradigm also requires systemic changes focused on social, economic and sustainability aspects. Within the scope of Industry 4.0, digital technologies are a key factor in interconnecting information between the physical built environment and the digital virtual ecosystem. The most advanced virtual ecosystems allow to simulate the built to enable a real-time data-driven decision-making. This Book Series promotes and expedites the dissemination of recent research, advances, and applications in the field of digital innovations in the AEC industry. Topics of interest include but are not limited to:

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Preface

Industry 4.0 is taking its first steps in building construction trailing the increasing digitization processes. Learning from industrial methods, Additive Manufacturing, also known as 3D printing, is being explored in construction in various fields, scales and purposes. Research on this topic has achieved a progress state, which soon will allow its' common use. Advantages are clear in construction processes optimization: the production time of both construction elements and building itself is drastically reduced. The integrated accomplice link between design and manufacturing allows a great freedom in form design, whereas various construction phases are dismissed: precast is avoided, reducing execution time and materials, labor time and costs hence CO₂ footprint is mitigated. Materials, technologies, methodologies (product design, building process planning) and performance have been explored by scientific research helping industry in order to bring innovation to professional fields. There are still challenges to reach and research is absolutely necessary and a priority. In this volume a set of papers is gathered to reveal the latest achievements, striving to collect the cutting-edge of today's knowledge.

Porto, Portugal
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Florianópolis, Brazil

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How 3DPC Will Transform Architectural Design



João Teixeira , Amaia Zuazua-Ros , Manuel Jesus , Bárbara Rangel ,
and Ana Sofia Guimarães 

Abstract Industry 4.0 has pushed construction to adopt processes that optimize the manufacturing of customizable solutions. Prefabrication, is beginning to understand that 3D Printing (3DP) with cementitious materials may open a new and wide range of options both formal and chromatic in customization, avoiding complex form-works, reducing costs and manufacturing time. Certified products are demanded, but it is obvious that there is a growing desire for tailor-made façade solutions, especially in its plasticity. Façades with designs, colors, and textures may thus overcome the execution constraints, narrowing the manufacturing process to the architectural conception and design process. In 3D printing, design process and its fabrication are engaged, enabling a great formal freedom and precision in the information transfer from drawing to its construction. The creative process is directly linked to the constructive process, bringing design closer to its materialization. Matter responds to form and form is designed by the matter capacity. This technology thus seems to be the ideal solution for the audacious design forms yet optimizing the constructive process.

Keywords Architecture · Building technologies · Customization · Digitalization · Materiality

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1 Introduction—Materiality in Architecture

In architecture, materiality is more than a physical aspect, it is the link between the building and the surroundings [1]. It is the limit between interior and exterior, private and public, light and shadow. The volume materialization is the skin of the building, revealing its face or “personality” with color texture, volume and even smell. The building envelope expose its identity, communicating the objectives and wills in its characterization. Within its formalization, a message is disclosed in the architectural design and materialized in its construction. This message that uncovers what the building wants to be, mirrors the technologies developments of its era. Roman Empire spread its power optimizing the construction process with stone overcoming itself in the Parthenon dimension. The walls were ripped in the gothic age, when the support given by the foothills was discovered. The skyscrapers were born when the structural strength of steel was disclosed. The concrete was the new stone which gathered sculpture and architecture in 60’s brutalism started by Le Corbusier. What design language will come out from the 3D printing in construction?

To understand how come this transformation is starting to be done it is important to understand the straight connection between technology and architecture in its time history, culture, and social challenges. This correlation is expressed in various forms ensuing what we see and what the building “wants to be”. Its’ physicality is revealed through materials’ matter, offering an immaterial meaning through the user’s interpretation. The value of this experience depends on architecture sensibility in unveiling the culture and social challenges of its time, through the combination of shapes, light, textures and colors. The right proportion between them, will define the user’s perception, the building atmosphere, as Gernot Böhme concept defines, the immaterial side of materiality [2]. For Peter Zumthor, atmosphere is an emotional sensibility, an inner perception, telling us that we should or should not see or perceive, a feeling that happens instantly in the moment of its experience [1].

Materiality design is the building soul conceived by the architectural process qualification and the technological quantification, giving the materials an immaterial meaning. Throughout history, creative thinking challenges technology to find or reinvent new materials as well as the emergence of new methodologies that leverage the creative thinking. Stone construction is one of the oldest examples of this evolutionary process. In Ancient Rome, it was necessary to build larger public structures due to the cities’ growth and the need to connect them. The arch offered the capacity to increase the structural bearings, reducing the material quantity and with its juxtaposition the building height could be raised, enabling constructions such as: coliseums, aqueducts and bridges. Romanesque architecture was characterized by growing structural vaults to reach wider interior spaces, necessary to accommodate the maximum number of believers inside the cathedrals. The Gothic buildings broke height records adopting ogival arcs, rib vaults and flying buttresses. Allowing higher constructions, the weight was transported to external structural elements. The large colored windows, opened the walls materializing the Gothic social/religious concept of “God is light”. These examples demonstrate that design materiality of each era

is marked by the constructive knowledge of that time, reviling the way architecture and technology build the answer to solve society needs.

In this chapter, an analysis of the materiality concept in architecture design, through technologies aesthetics is proposed. Parsing some examples in modern and contemporary architecture design methodologies, the intrinsic connection between material and form is discovered. Considering these landmarks and observing some contemporary attempts of this technologies, it is pretended to understand what Industry 4.0 technologies, namely 3D Printing Construction (3DPC) can proffer to today's architecture.

Mies van der Rohe combined concrete and steel to build structures with large spans, using the transparency of glass to produce the physical limit between interior and exterior. Glass was not only a physical barrier between interior and exterior but an element that combined and articulated the interior elements with vibrant exterior reflections, and the outside with reflections of the interior [3]. Glass worked as a plastic element in Mies' architecture, showing the careful material combination in the large interior open spaces [4]. Advocate of the concept "Less is more", the minimalism of his architecture was only possible thanks to the use of industrial materials in its full potential, combining the glass lightness with the robustness of concrete and steel. The German Pavilion for the 1929 International Exposition in Barcelona can illustrate all these principles.

As Mies van der Rohe, Le Corbusier was influenced by technological advances in industry, believing that the construction should follow the same steps, guided by The Five Points of a new architecture [5]. Opposing to art-nouveaux, ornament was an "enemy" and industry an ally to create the "machines à habiter", the perfect environment for the new modern Man growth. After the Second World War, the industry was broken, and some materials were not available. Faster and cheaper building processes were needed to rebuild the destroyed cities urgently. Concrete was the first choice. The building uncovers its construction and materials are used in its purity showing what is made of, its capacities, the basis of brutalism. The function is revealed in the form, the structure is part of that form and the material is explored to characterize its expression [6]. Exposing the structure as a plastic element the concrete roughness was explored to find its various textures and colors. The *béton-brut* was the material of election, but other materials as stone, wood or terracotta or brick [7] were used by architects like Louis Khan in USA.

In *Unité d'Habitation* (Fig. 1) the first Le Corbusier's brutalist building [7], the structure and its materiality define the geometric composition and its textures characterize each different functional space: the vertical texture left by the mold reinforces the pilotis robustness; in the roof the Modulor printed in the concrete walls is part of the playground. In *Notre-Dame du Haut* chapel the organic dynamic sculptural form, explores the structural and sensorial capacities of reinforced concrete: the rough white sprayed concrete (*gunite*) of the walls finishing's contrast with cold *béton brut* of the floating organic roof, Fig. 2 [8]. Corbusier brought to architecture his artistic sensibility, featured in the exploitation of color, light of textures of daring sculptural forms hence functionally rational. What if Le Corbusier had the possibility to make a building with a system that could transform the drawings directly to the construction?

Fig. 1 Pilotis at the Unité d'Habitation, Marseille by Le Corbusier. Where the typical texture of béton brut is clearly visible (credit: Med Mor)



Fig. 2 The chapel Notre-Dame du Haut, Ronchamp, by Le Corbusier (credit: Scarlet Green)



Frank Lloyd Wright understood architecture as a living organism, that should be part of its natural environmental and its construction system defined by the landscape materiality. The building is the result of the conveying harmony between Man and Nature, the Organic Architecture [9]. Learning from ancient Persian, Byzantine, Chinese, Japanese and American Pre-Columbian cultures, hence exploring the capacities of new materials and innovative system, the link between Nature and Modernity was materialized with the use of local materials and ancient technologies combined with innovative systems like glass or concrete. At Taliesin West, FL Wright used local desert stone in the concrete structure, discasing the building in its environment while offering large spans and great skylights. The building is undercoverd in the surroundings and the landscape is brought to the interior atmosphere, as shown in Fig. 3 [10].

The architects pursuing of the materials capacity is evident in several works as a way to extreme the forms or to find the building aesthetics. In the Fallingwater House the concrete is challenged to materialize the balanced horizontal plans hanging over the water. In the set composed by, Ennis House, Hollyhock House, Millard House, Storer House in California, inspired by Pre-Columbian architecture, the concrete

Fig. 3 Exterior desert stone masonry in Taliesin West (credit: John Fowler); and interior desert stone masonry in Taliesin West, where stones larger than those exposed outside the house can be seen (credit: Artotem), respectively



is used in the prefabrication of the textile blocks, a constructive innovation system design and patented by himself that merged structure and aesthetics (Fig. 4). It is an example of his concern and responsibility to connect the design with industry for mass customization of the American House [7]. Imagine that FL Wright had a system that could transform the materials of each site in a mortar? What would be the language he would have encountered?

Gaudi also explored the potential of the materials aesthetics and structural capacities. In his atelier, structural models of each building were made to encounter the materials' limits and therefore its formal capacities. The intense study of the natural organisms' structures, with his eclectic background not only in architecture but also on design and engineering offered him the possibility to design architecture with a deep knowledge of its construction materials and techniques: Concrete was studied and experimented intensively to design outrages forms [11]. Fragmented small ceramics, the trencadis technique (Fig. 5), allowed to fill the complex surface structures with different colors and textures, bringing it closer to the Nature vibrant dynamism [12]. What if Gaudi had a technology that could realize almost any form without any formwork or molds? Would have Sagrada Familia be already built?



Fig. 4 Different views of Ennis House, designed by Frank Lloyd Wright. The images show the chromatic homogeneity given using the same constructive system in all building elements (left side picture credit: Pom' and right side picture credit: Kyle Magnuson)

Brazilian architecture and engineer are wildly known for their tradition of using concrete in buildings with disruptive forms. This complicity made possible to build Oscar Niemeyer's drawing curved forms inspired in the Brazilian landscape as seen in Fig. 6 [13]. Imagine he had a way to directly print his drawings in the real scale!

Lina Bo Bardi, explored concrete structural capacity to lift MASP from the ground making a gathering social common public multifunctional open space (Fig. 7). She explored the materials capacity to emphasize the purity of architecture, the "Arquitetura Pobre". Reinforced concrete gave the possibility to propose outstanding forms characterized by texture, color and light offered by the mold conformation. In SESC Pompeia Factory, the wood formwork rawness gave the concrete the stripped ornament textures as seen in Fig. 8 [14].

What if Lina Bo Bardi had the possibility to enhance this will of exploring the materials tectonics with a system that could print concrete with various forms and textures?

During the 70's, in the United Kingdom, Denis Lasdun adopted concrete to rationalize the three dimensions of the volume geometrical composition highlighting the structure as a sculptural element emphasized with the molded variety of each element (Fig. 9). In the London National Theatre, the articulation of the hanging horizontal volumes interiors uncovers the necessity of a vertical support. In its interior various formwork geometries were made to characterize the wall in each functional space, creating an organic geometric surface with different depths, such as a natural stone (Fig. 10). What could have he designed knowing that molds weren't needed, and texture could be made directly from his drawings?

Alison and Peter Smithson discovered in different materials the expression of the construction purity, the delicacy of the handcrafted stone walls (Fig. 11), and the concrete capacity of repetition modularity (Fig. 12). What if they had a 3D printer to explore the materiality of concrete with other materials?



Fig. 5 Several pieces from Park Güell, where trencadis technique was used: (top left) Palau Güell's chimneys (credit: gandalf3007); (top right) "El Drac", a lizard (credit: Nacho); (down left) a detail that shows the vibrant colors used by Gaudí in his constructions (credit: Italo Canessa); and (down right) Sagrada Família (credit: z0rc), respectively

When Marcel Breuer was in USA, explored the concrete structural capacity to design complex mathematical geometries to discover the building monumentality. In Church and Rectory of St Francis de Sales, the walls were defined with the soaring hyperbolic paraboloid emphasized by its formwork (Fig. 13). In Fundació Joan Miró in Barcelona, Josep Lluís Sert combined different textures in the surfaces with board-marked concrete using different directions in the precast panels in the mathematical intersection of pure volumes (Fig. 14). What if both architects, that used mathematical

Fig. 6 Pampulha Modern Ensemble: Oscar Niemeyer's draw (via designKULTUR), and the same building, Church of Saint Francis of Assisi, a building part of Pampulha Modern Ensemble (credit: Régine Debatty), respectively



Fig. 7 Wide span of the MASP building for people interaction (credit: Leo)



Fig. 8 Bridges between the two SESC buildings, with pronounced formwork textures (credit: Andreia Reis)



Fig. 9 Set of concrete volumes that make up the exterior structure of the London National Theatre (credit: Rev Stan)

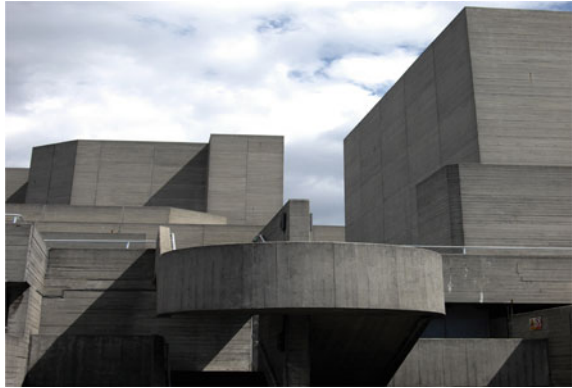


Fig. 10 Texture developed by Denys Lasdun, in the interior of the London National Theatre (credit: Paul Wilkinson)



Fig. 11 The solar pavilion by Alison and Peter Smithson (credit: seier + seier)



Fig. 12 The Robin Hood Gardens by Alison and Peter Smithson (credit: Steve Cadman)



Fig. 13 Church and Rectory of St. Francis de Sales (credit: Seth Tissue)



Fig. 14 Fundació Joan Miró in Barcelona (credit: Daniel Lobo)



geometry to define building forms had a tool that translated these complex geometries directly to construction?

Herzog & de Meuron are nowadays, exploring the materials as architectural expression, contrasting the material rawness with simplified forms like in the Stone



Fig. 15 Exterior of Museu Blau, where blue shades over the entire building are seen (credit: Rick Ligthelm), and mirrors detail where blue shades are also explored (credit: Marat Nevlyutov), respectively

House. In the Museu Blau, in Barcelona, several materials were combined making an impressive play of textures and surfaces, juxtaposing roughness and smoothness, light and dark or big and small. With the high contrast of materials, shades of blue take over the entire building, creating an element of unification (Fig. 15). Are they proposing now additive manufacturing to build its works?

In Peter Zumthor's design process is crucial in the building materiality definition. The local technological and constructive traditions work together with new materials, appealing to senses, such as smell and audition. These principles are expressed in Chapel Bruder Klaus, where the building materiality is coined by the design process. The formwork was made in the interior with logs from local trees to define the internal pyramidal shape. Outside, by contrast, the concrete was made with local agglomerates, was formed with plain and smooth formwork (Fig. 16). After the concrete dry, the inside wood structure was burned, giving the interior a darkness illuminated by a top skylight, highlighting the texture left by the wood (Fig. 17). The darkness left in the interior by the burned formwork stands out from the earthy tones of the smooth texture of the exterior, Fig. 18 [15]. Is he using automated manufacturing systems to encounter new immaterialities?

Since the beginning of his career, Álvaro Siza following Alvar Alto or FL Wright design process of finding in construction the building tectonics [15], experimented the sculptural capacities that concrete could offer in its robustness, tactile characterization and formal possibilities [7]. In Piscina das Marés Swimming Pools (1966) the long plain wall respectfully contrast with the infinite organicity of the rocks. In Ibere Camargo Foundation, in Brazil (2008) the structure is a sculptural plastic element in white exposed concrete taken to its limits suspending the detached ramps, Fig. 19 [16]. What if he had a gigantic pen that could directly build his imagined sketches?



Fig. 16 Chapel Bruder Klaus exterior, where it is visible the layered concrete with earthy tones (credit: seier + seier)



Fig. 17 Chapel Bruder Klaus interior wall (credit: seier + seier)

In the 90's of the past century, the Computer Aided Design (CAD) technology arrival allowed to reduce the distance between design and industry. In architecture, two architects stood out by exploring the strengths of Digital Design (DD) to materialize new and more complex geometries, Frank Gehry and Zaha Hadid, mentors of Deconstructivism in Architecture. Frank Gehry has been the key driver for introducing Computer-Aided Design (CAD) in architecture, guided by twisting



Fig. 18 Top of the Chapel Bruder Klaus where the light emphasizes the texture left by the burned wood (credit: seier + seier)



Fig. 19 Ibero Camargo foundation by Álvaro Siza, building façade where is visible the suspended ramps (credit: Secretaria Especial da Cultura do Ministério da Cidadania) and building exposed white concrete detail (credit: Alexandre Pereira), respectively

curvaceous forms, whose structural calculation was only possible with the use of 3D modeling software, CATIATM [24]. Examples are the unusual and already historical buildings like Walt Disney Concert Hall (1987–2003) or Guggenheim Museum Bilbao (1992–1997). To cover the Guggenheim Museum Bilbao structure, Gehry used titanium, a very expensive material used by aerospace industry (Fig. 20), while in Walt Disney Concert Hall he used steel.

Zaha Hadid used digital technologies to design sophisticated curved forms, based in nature [17], as is possible to be seen in the Heydar Aliyev Centre (2012) in Fig. 21 (left). The smooth surface was achieved using Glass Fiber Reinforced Plastic (GRP) panels attached to a complex structure (Andrew Watts 2016; King and Mungall 2012). Zaha Hadid Architects Computation and Design Group (ZHA CODE), with Block Research Group (BRG) from ETH Zurich developed Striatum bridge a 3D printed concrete in Venice (Fig. 21 right). It is composed by 53 printed hollow blocks with 50 layers each. This is just the beginning of using 3DPC for this studio.

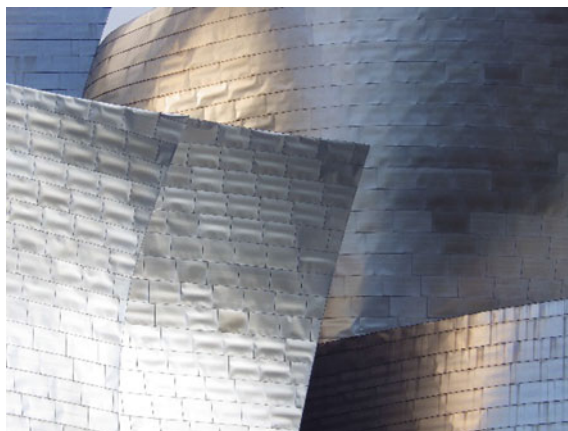


Fig. 20 Detail of titanium surface on the Guggenheim Museum Bilbao (credit: Puffin11k)

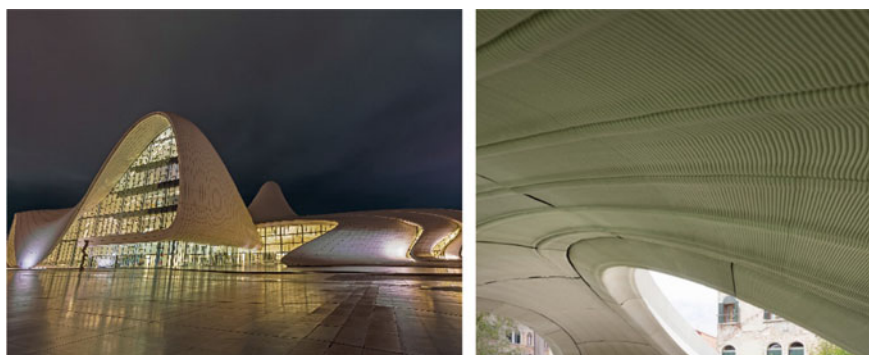


Fig. 21 Heydar Aliyev Centre structure, covered by GRP panels (credit: Ali Sabbagh), and Striatum bridge detail (credit: Naaro), respectively

Architects like Le Corbusier, Niemeyer, Marcel Breuer and Álvaro Siza proved that it is possible to shape reinforced concrete in several types of forms, though, until now the limits of these forms depend on the structure capacity of the materials. When the structures are in concrete, the limitation is also imposed by the formwork capacities, and this formwork corresponds to about 40–60% of the structure cost [19]. By introducing, 3DPC this cost can be reduced, making possible to create audacious forms with less limitations even in buildings with lower budgets yet optimizing the constructive process.

With this short review of some examples of how materiality/form is approached by some architects, from Le Corbusier to Zaha Hadid, is possible to understand that architecture and innovation in building technology go hand in hand. Many projects remained unbuilt, unfinished, with budgets higher than planned, suffering changes in materials or in the original project. Over time, some architectural challenges were

solved using innovative constructive processes and new materials, however, there were challenges that were too ambitious for the technologies and materials of the time. As one of most of the most paradigmatic examples of this mismatch is the Expiatory Temple of the Holy Family, the emblematic building of Antoni Gaudí, a construction with extremely complex geometries and ornaments, which, despite the architect's creativity and his technical-scientific capacities, presented constructive challenges for over 100 years. This design was ahead of its time and now the 3DPC is starting to be used to materialize the project. Its design, born in 1882, was born more than one century before the technical possibility to make it (Nunnally 2013)!

Having this in mind, in Fig. 22, a synthesis of the examples analyzed of architecture developed flowing the material capacity to reach outstanding forms is made, linking them with technology used. In all these examples is possible to perceive a will of logging the technology as a design language, not only in color or texture, but also with the structural capacity of reaching owing forms. F. L. Wright explored different materials to create the construction modules for each building geometry. Le Corbusier used concrete rawness transporting modern art to common life. As Le Corbusier, Peter Zumthor believed that a building must be real, showing the materials and methods by which are materialized [1]. Imagine if they had the possibility to materialize their design directly in the building site!

It is possible to say that technology innovation is driven by these forwarding ideas, and when is spread in the construction market, the design language and building formalization is transformed. Now that we are assisting to the birth of the 3DPC is possible to ask: what will be the influence of 3DPC on the plasticity of buildings? How will the architectural language be transformed?

To continue these analyses of the design transformation resulting from the technological advances of 3DPC, we will have to wait for audacious stakeholders to put architects and engineers working in printed buildings.

2 Digitalization Design in Construction

To understand what the consequences of the link technology/architecture are now a review on the main Industry 4.0 (I4.0) tools used in design process is made. The construction industry is experiencing many changes in recent years due to the introduction of new digital technologies brought by I4.0, which is pushing the sector to be more prone to change than it has been during the last half century. These technologies have the capacity to make the production system more effective, connecting all the life cycle phases and its stakeholders. Examples of these technologies are: Materials Science, Artificial Intelligence (AI), Internet of Things (IoT), Big Data, Digital Design (DD), Autonomous Vehicles, Cloud Computing, Digital Twin (DT), the Fifth-generation Cellular Network (5G), Robotics and 3D Printing [20, 21]. How are they transforming the design processes?

The first methodological change in the design process is made in the way that objects are drawn. Instead of making 2D drawings with the various views of the

	Coatings	Material as Matter	Technique
1882			Beginning of the construction of the Expiatory Temple of the Holy Family
1914			Park Güell - Gaudí Structure: Concrete, stone. Texture: Trencadis, stone.
1923			Notre Dame du Raincy - Auguste Perret Structure: Reinforced concrete. Texture: Béton brut.
1924			Ennis House - Frank Lloyd Wright Structure: Textile block systems. Texture: Geometric Pre-columbian elements, customized by the textile block system.
1929			Barcelona Pavilion - Mies van der Rohe Structure: Reinforced concrete and steel. Texture: White painting, glass and others.
1931			Villa Savoye - Le Corbusier Structure: Reinforced concrete. Texture: White painting and glass.
1937			Taliesin West - Frank Lloyd Wright Structure: Desert stone masonry. Texture: Different sizes of desert stone and concrete/mortars.
1944			Pampulha Modern Ensemble - Oscar Niemeyer Structure: Reinforced concrete. Texture: Tiles, stone and white painting.
1947			São Paulo Museum of Art (MASP) - Lina Bo Bardi Structure: Reinforced concrete. Texture: Béton brut, red painting.
1952			Unité d'Habitation - Le Corbusier Structure: Reinforced concrete. Textures: Béton brut.
1955			Notre-Dame du Haut - Le Corbusier Structure: Reinforced concrete and sprayed concrete. Textures: White stippled surface (lime) and béton brut.
1959			Upper Lawn Pavilion: "Solar pavilion" - Alison and Peter Smithson Structure: Reinforced concrete and wood. Texture: Stone, wood, zinc.
1966			Leça Swimming Pools - Álvaro Siza Vieira Structure: Reinforced concrete. Texture: Béton brut.
1969			Fundació Joan Miró in Barcelona - Josep Lluís Sert Structure: Reinforced concrete. Texture: Béton brut and prefabricated panels.
1972			Robin Hood Gardens - Alison and Peter Smithson Structure: Reinforced concrete. Texture: Béton brut.

Fig. 22 Heydar Aliyev Centre structure, covered by GRP panels (credit: Ali Sabbagh), and Striatum bridge detail (credit: Naaro), respectively

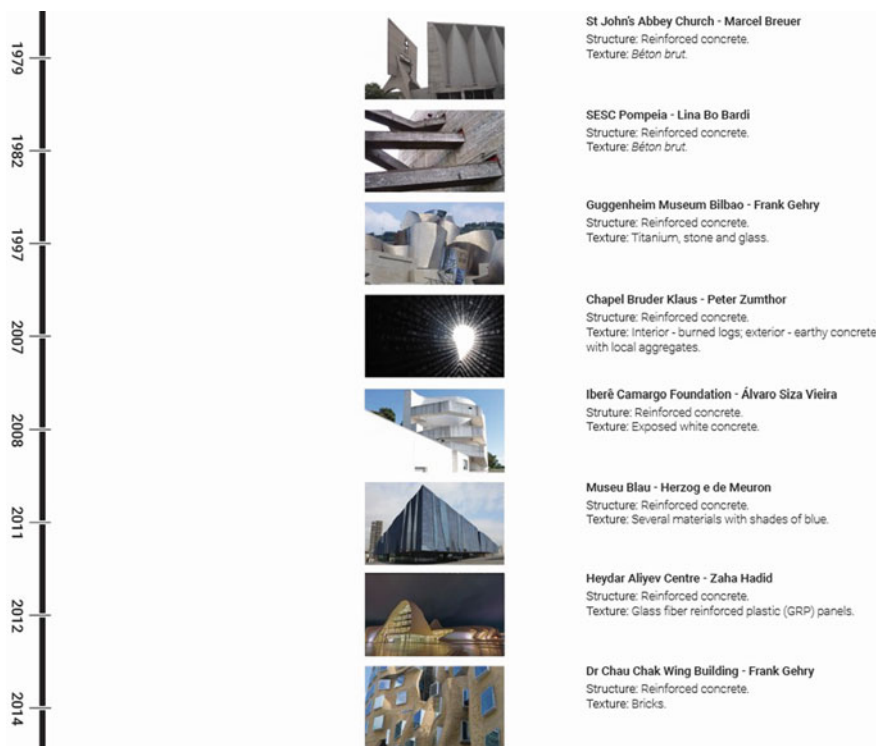


Fig. 22 (continued)

object, the design starts with a 3D digital model that will have its information. This model improves the interaction between architects, designers, engineers and production, creating greater innovation and more rapid action between all stakeholders for a collaborative work process. This 3D model is obtained through Digital Design (DD) tools, that offer various solutions to different areas like: design through computer-aided design (CAD); engineering using computer-aided engineering (CAE) and finite element analysis (FEA); manufacturing applying computer-aided manufacturing (CAM) software, which it is the information of the 3D model that tells a machine how to make the product; and management through Product Data Management (PDM) software, that manage each element of the product throughout its life cycle [21, 22], like Building Information Modelling (BIM) in construction industry [23].

DD had a great role in the possibility to develop complex architectural forms like Gehry's. In his architectural firm DD was successfully introduced with CATIA software in the 90ties, used only by the aerospace industry at the time. This software was crucial to turn the Gehry's sculptural architecture buildable. In the beginning DD was not part of the creative process, it was just used as a tool to materialise hand-sculpted shapes [24].

Today DD techniques, as Parametric and Generative Design, are currently part of design process to achieve detailed and functional structures with deeper definition to be passed to the building process. Parametric Design (PD) is a design process based on algorithms that allow the creation of highly complex solutions, virtualizing geometries into a 3D model [24–26]. Generative Design (GD) is an iterative process, where an algorithm creates several design options according to the selection criteria set by the user, being an example of AI application during the design process [27–29].

Zaha Hadid's architecture studio has been using Generative Design tools, namely the Grasshopper plugin from the Rhinoceros software, to create designs inspired by nature, with extremely efficient solutions and highly complex geometries [17]. In 2005, Dr. Kristina Shea, who is now a professor at ETH in Zurich, wrote: "Integrated performance-driven generative design systems are aimed at creating new design processes that produce spatially novel yet efficient and buildable designs through exploitation of current computing and manufacturing capabilities." Due to its offers the possibility to design geometries with freedom easily combined with additive manufacturing technologies.

There are also other software's that enables the monitoring of the product life cycle even during the design phase. In the construction industry, Building Information Modeling (BIM) comprises digital information of a building throughout its life cycle, containing geometric and semantic data for each building element or material. It enables the automation of collision checks, quantity evaluations and the generation of different models (Water Distribution Network Design, Structural Design, etc.). The current improvement of the quality and efficiency in the Building and Construction industry by means of this tool could also be extended to additively fabricated building components (Paolini, Kollmannsberger and Rank 2019).

However, there are still some challenges to overcome regarding BIM application to Additive Manufacturing, due to the lack of data interoperability between BIM platforms and Additive Manufacturing systems (BIM platform needs to be capable of interacting, analyzing, and controlling the components of the 3D printer). After this, it will be possible to take full advantage of AM techniques (Paolini, Kollmannsberger and Rank 2019).

Advances in DD and automation drove industry to advanced production systems. Currently, different types of these advancing manufacturing processes stand out in construction industry, like computer numerical control (CNC), robots, and additive manufacturing (AM). Despite different construction processes (additive or subtractive), all these technologies, establish a direct link between the digital model and the production system, through CAM files, increasing the accuracy and the speed production. Accordingly, these technologies are changing the design processes and forms in architecture.

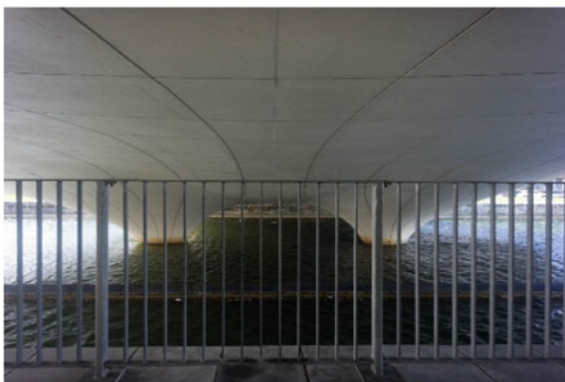
The complex geometries raised in architectural designs have involved high economic efforts due to their high cost of labor. Several examples can be found in the work of two renowned architects recognized for their formal organic proposals and complex geometries such as Zaha Hadid and Frank O. Gehry. Two studios that have worked from the digital model for decades, the materialization of their architecture

has been carried out due to multidisciplinary work with other areas and the parallel development of advances in CNC and robotics, among other technologies.

Despite its wide use in wood construction [30], CNC technology has been applied, frequently, in free-form concrete elements, using material subtraction, to materialize the formwork where then concrete will be cast [31, 32]. The Spencer Dock Bridge, in Dublin, designed by Amanda Levete Architects (Fig. 23), is an example where more than 100 Expanded Polystyrene (EPS) formwork elements were milled to shape the bridge geometry [31, 33]. Despite the variety design possibilities and smoother surface finish, these methods are unsustainable due to the formwork single use, creating high costs and waste.

Robots are a synonym of automation and productivity in several industry sectors, as automotive. Japan started to explore its inclusion in construction industry in 1970, firstly to increase quality in prefabrication and later, in 1980, on site construction [34]. Over the years, robots have been introduced, on site and off site, with considerable functions and materials: spraying [35], assembling [36, 37] painting, inspection, cutting and milling, casting, additive manufacturing [38, 39], etc. Currently, the Robotic Fabrication Laboratory (RFL), a multi-robotic system in ETH Zurich, is one of the best examples of research in robotics for architecture and construction.

Fig. 23 Imagens of Spencer Dock Bridge, where more than 100 EPS elements were assembled to build a smooth concrete surface (credit: William Murphy)



Composed by four six-axis robots, assembled in a gantry system, this structure allows the use of the four robots throughout the building, a complete system that allows the study of different projects related to digital fabrication [40]. This great diversity of projects has contributed with innovative approaches, using robotic systems, to develop digital construction, are examples: Eggshell, Mesh Mould Prefabrication, Timber Assembly with Distributed Architectural Robotics, etc. [39]. The Eggshell project is an approach that allow the fabrication of non-standard reinforced structures, printing a 3D recyclable formwork using a Fused Deposition Modeling (FDM) 3D printer. This technique requires the synchronization of the two processes, printing and casting, since it occurs simultaneously, the inclusion of 3D printing with a recyclable material in formwork fabrication allowed to reduce waste and costs, when compared with milling and cutting systems [38].

Additive Manufacturing (AM), commonly known as 3D Printing (3DP), has experienced strong growth in construction industry over the past decade, especially in techniques that used material extrusion. Several types of structures (houses, bridges, reefs, urban furniture, panels, sculptures, etc.) were printed, proving its potential for future applications (BuiltWorlds Voices 2016; Cor 2019; Twente Additive Manufacturing B. V. 2021; XtreeE | the large-scale 3D 2018). Despite the great potential of the previous technologies 3DP is the only one to directly link the 3D model to the final product in concrete, as it does not need formwork in the process. The material is stacked in layers, creating a layered texture which can be controlled changing the 3DP printing parameters as nozzle geometry and size. Although some approaches treat this texture as a defect, we believe that it is an element that should be explored aesthetically, working as a differentiating element of 3DP and following the thought of Le Corbusier and Peter Zumthor that a building must show the materials and methods by which are built. An example of this application is the 3D printed house designed by Houben and Van Mierlo Architecten for Project Milestone [45], Fig. 24.

Parametric and Generative Design combined with digital construction techniques have been extremely important for mass-production environments as effective enablers of I4.0 approaches in the Building Industry. Its wide use has brought the concept of “Digital Materiality”, which has been described by Gramazio and Kohler

Fig. 24 3D printed house project designed by Houben & Van Mierlo Architecten for Project Milestone. *Source* (3DPRINTEDHOUSE, 2018)



as “the synthesis of two seemingly distinct worlds, the digital and the material, generating new, self-evident realities as soon as data and material, programming and construction are interwoven [46]. Once again, the Expiatory Temple of the Holy Family still defies the current technologies. These innovative constructive processes are now accelerating its construction [47], linking the Gaudís’ complex design to its production.

3 Customization and Digital Design

The building industry is known as an engineer-to-order industry, where the process only begins to work once the product order is purchased [48]. This way of operating, deep-seated in the sector, creates difficulties when it comes to standardizing processes. The advances in standardization and prefabrication made from the 1950s have provided effective solutions to improve process efficiency, however, they have not been widely embraced, unlike other sectors such as automotive. One of the main reasons for this lack of success can be recognized in the customization limits that affect standardized and prefabricated products, which might not fully meet the client’s needs [49]. Thus, at this point, it should be remembered that the uniqueness of the projects is an intrinsic characteristic of the architectural design process. However, digitization can improve and optimize processes, making customization arise at a lower cost.

As seen in these analyses, the impact of the digitalization in the construction industry together with the advances in technology are opening a new paradigm in terms of processes and product development arising from the relation between the design conception and the building matter [50]. Shortening the gap between design and production is opening new opportunities to create and manufacture complex forms both in architecture and design, particularly with 3DPC technologies.

This digital transformation gives opportunity to the expansion of mass customization (the combination of mass production with customized outcomes with a competitive price) to become an increasingly tangible reality in the construction sector. This concept might be considered an oxymoron [51], seeing that “mass” and “customization” can be contradictory. But as a building is not a typical industrial product easily reproduced, mass customization can be considered as a win–win strategy that benefits both customers and companies [52] increasing the construction process sustainability. Molds are exempted, the construction process shortened, the used materials reduced and, as a result, the all-process waste severely diminished.

At this point, two examples of the use of precast concrete panels are shared to highlight the potential of the use of 3D printing as a precast manufacturing process to lower the cost of customized concrete structures: the Dusseldorf building complex Neuer Zollhof, designed by Frank O. Gehry (Fig. 25) and the Roca London Gallery by Zaha Hadid Architects. In the first one, completed in 1999, the façade was designed following generative processes to create the curves articulation and the precast molds

Fig. 25 Neuer Zollh of building complex. The surface of the precast concrete elements did not remain visible (credit: Alexandre Prevot)



were made of extruded polystyrene milled formwork. They were open molds, thus, the control of its thickness was not homogeneous [53].

Among the works of Zaha Hadid Architects, the Roca London Gallery (Fig. 26), completed in 2011, is a manifestation of the potential of parametric design and manufacturing through the use of precast Glassfibre Reinforced Concrete (GRC) for complex shapes. The 236 indoor and 36 façade GRC panels were composed of two layers of concrete mortar and a honeycomb shape mesh [54]. In this case, unlike the previous example where other claddings covered the façade, the effort made in the panels creation is reflected in the final finishing of the building.

Once having noticed these two cases and considering customizing as the action to build, fit, or alter according to individual specifications, customization does not seem as a challenge in architecture: as mentioned before, the sector itself has always produced tailor made products. However, the drawbacks that these manufacturing processes carry (such as the high cost) pose a challenge that involves shifting the construction processes. 20 years passed, mass customization can have a sustainable answer connecting matter and design through technology. Additive manufacturing has shown to have several advantages, including the effective use of ever-decreasing material resources, given its advanced material use optimization and distribution



Fig. 26 Precast concrete process of the Roca London Gallery (Peck, 2014), and building façade (credit: ROCA), respectively

Fig. 27 Smart slab on
EMPA NEST, ETH Zürich
(credit: Trevor Patt)



methods. With such a fabrication process it is possible to generate complex shapes without additional production complication or costs increase [55].

Research Labs and Industry are working together to find feasible solutions for the construction market. The first stage, was seeking the formwork optimization with AD technologies and now that this first stage was exceeded, with that knowhow some experiences are now being made to bring AM to fabricate the façade itself. Today most of the applications of AD for prefabricated concrete rely on the use of formwork 3D printing. This is the case of the Smart Slab built by the ETH Zürich in 2018, Fig. 27, where a parametric construction method using different technologies was developed for the construction of an optimized concrete slab using 3D printed formwork for casting or spraying concrete in any shape [56, 57]. This demonstrates the ability of 3D printing to overcome the geometric limitations of traditional methods for formwork fabrication. As a result of this work, the group also addressed the importance of the recyclability of the custom formworks, being this a key point to reduce the carbon footprint of the overall process.

In this respect, the method developed by FreeFabTM is proposed as an alternative given the recyclability of its formworks. Their non-structural curved concrete panels are made using 3D printed wax-based molds, where the concrete is poured and once hardened, the wax is melted off and 99% of it is reused for another formwork print, Fig. 28 [58]. This method has been applied for the finishing cladding in the

Fig. 28 GRC panels from
FreeFabTM (Laing
O'Rourke 2017)



Fig. 29 Elizabeth line stations in London (Crossrail 2017)



construction of Elizabeth Line stations in London Underground network in 2017 (Fig. 29).

On a next stage are the façade elements directly 3D printed as a final cladding solution. By eliminating the use of molds, the manufacturing process is optimized and both, the use and waste of materials are reduced. The existing built applications of 3D printed concrete panels are less common than those precast options explained before. At the present time, there are no architectural references of buildings constructed with these panels as cladding material. However, the recently made experimental studies are small scale prototypes that serve to demonstrate the potential of this use of mortars additive manufacturing. An important feature of this solution refers to the aesthetics of the elements since the construction process is present and dominates the final textures of the finish product. In turn, it allows exploring the creative potential offered by 3D printing through parametric design when it comes to providing countless shapes and textures. The company Twente Additive Manufacturing (TAM) is a good example of this exploration (Fig. 30).

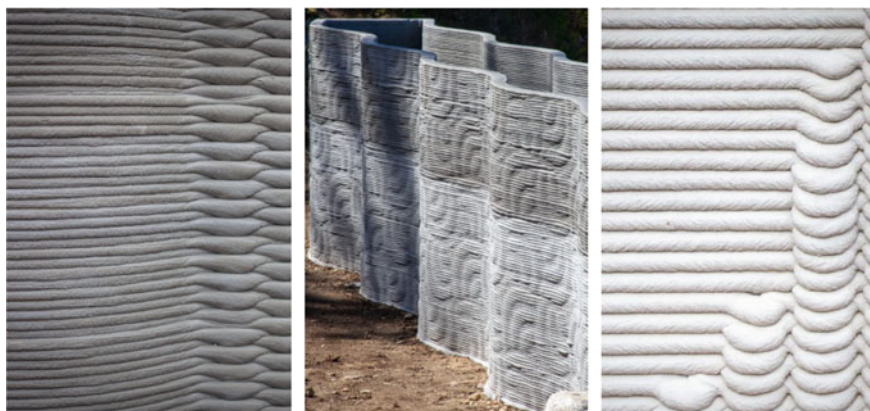


Fig. 30 Different texture studies designed by TAM [41]

4 The Role of Digital Design in Biomimicry

In recent years, the tendency to have nature as a source of inspiration and reference in the face of human challenges has grown considerably. The attempts to recreate organic forms in architecture, as well as the concern to achieve sustainable processes and an optimal use of materials, lead us to one of the topics that has been on the rise of these experiences in the last decade and that transversally affects all fields of knowledge, which is biomimicry. Janine Benyus, biological science writer, defines biomimicry as “learning from and then emulating natural forms, processes, and ecosystems to create more sustainable designs”. This trend has aroused interest in numerous areas of research for its application, and architecture has not been less. Biomimicry in architecture can be applied at many scales: urban metabolism, energy systems, passive design, optimized structures, new materials development.

Antonio Gaudí was one of the architects who used nature as an inspiration beyond the creation of organic forms. Known for the organic plasticism and naturalistic style of its architecture, he entailed a formal renovation of architecture in the twentieth century. At first, it may appear to be a simple formal imitation of natural motifs. However, as a result of working through inspiration in nature, he made decisions about bioclimatic behavior, used brick and tile (the most economical materials at that time), stone from local sources, waste or demolition materials and he optimized the structural design of its buildings. For all these reasons, some have considered him as the forerunner of sustainability and biomimicry in architecture [60].

Today this concept can be transferred to the building performance to respond to the big impacts of this industry, namely the energy consumption. In buildings, one of the elements to be addressed could be the building façade, since it is the border between the inside and outside environments and consequently allows significant exchanges of heat, affecting the inhabitants’ thermal comfort [61] and enabling substantial energy losses or gains during the use phase [62]. Thus, to understand what influences can be taken from nature, it is necessary to understand the actions that enable a good thermal performance: (i) reduce direct solar heat gain; (ii) consider intelligent shading devices; (iii) design efficient natural ventilation systems; (iv) make a proper material selection; (v) plan a good interaction between wall layers. Biomimicry has here an important role translating the natural skin structures to building façade design. The improvement of building skins has always been a constant challenge in architecture. The study area that aims to improve building skins efficiency exploring nature inspired solutions is referred as Bio-Inspired Building Skins (Bio-BS) or Bio-ABS, in the case of adaptive skins [63]. Those solutions, inspired by the environmental adaptation of plants, are of special interest due to the basic feature that characterizes both plants and buildings, which is the immobility. If we refer to the construction of buildings and their design process, there are few projects in which the concepts and project decisions based on biomimicry have been carried out from inception to final execution in a comprehensive manner.

Some animals use the earth’s deepness for cooling; in buildings, several passive cooling systems comprise underground airflow tunnels, as will be seen below [64].

Having this in mind, a significant challenge in Architecture is to design ecological cooling systems in buildings located in hot regions, where natural ventilation is considered as a crucial and economic cooling resource. To solve the hygrothermal built problems, the necessary actions to be taken should focus on the wall's structural layers and arrangement, new construction units, adaptive kinetic façades or manipulation in the design of building's plans [65]. The construction element that has the greatest impact on the exchange of heat and moisture is the building façade, as it covers the largest external area of a building. Thus, smart façade systems must be considered to improve the building's energy performance.

One of the most compelling examples of this is the secondary sunscreen installed over the thin skin of the glass façade of Al Bahr towers. The idea was developed by Aedas Architects that seek to avoid the strong sun rays of Abu Dhabi's very hot climate, where temperature may reach 49.2 °C. With this purpose, using AI they designed a responsive façade inspired from the adaptive flowers and the mashra-biya, a traditional Islamic lattice shading screen, commonly used for privacy and glare reduction. Each triangle, coated with fiberglass, folds and unfolds according to the sun's movement, as a way to reduce solar gain and glare, being closed in the evening. According to Aedas, the dynamic façade avoids the need of treated glass, also allowing for more visibility and a reduction of the use of artificial lighting and mechanical air conditioning. It is also worth mentioning that parametric software was used to predict the skin's operation regarding the sun exposure and movement during different times of the year (AHR n.d.).

Smaller scale studies have dealt closer to the action of biomimetics in the texture of the material itself. The study developed by Peeks and Badarnah examined the impact of surface texture on heat loss capabilities of concrete panels through evaporative cooling using morphological adaptations found in Nature like the cactus seen in Fig. 31 [66]. A similar study analysed the potential of concrete 3D printed tiles with complex geometries to improve the thermal performance in building envelopes, focusing on the air flow characteristics occurring near the outer surface of the tile [67], (Fig. 31).

An interesting approach of Biomimicry in 3D Printing was recently developed by Siam Research and Innovation Company (SRI), a Thailand-based cement manufacturer. Their façade panel called Triple S consists of Surface, Structure and Shelter design concepts, inspired in Thai folk handicraft, more precisely coconut leaf, taken

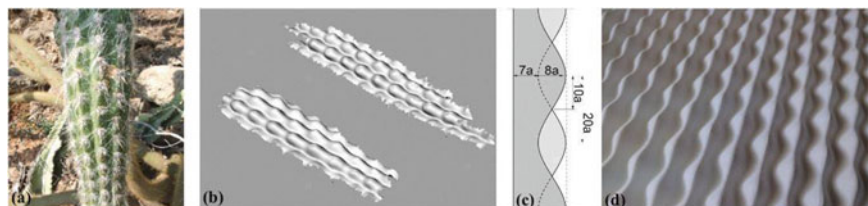


Fig. 31 Thermal optimization of concrete panels with geometry inspired by the cactus texture (Peeks and Badarnah 2021)



Fig. 32 Façade panels inspired by Thai traditional craftsmanship [68]

as the weaving pattern (Fig. 32). In contrast to normal practice, in this façade wall, the outer surface layer (the weaving pattern) may have the structural performance of the inner truss, performing in both aesthetic and structural functions. Additionally, this surface transformation results in less material consumed [68].

5 Conclusion

This growing trend on biomimicry approach in design defends that the study of the existing parallelism between Nature and building systems is needed for the identification of immediate opportunities that biomimicry offers for future research [69]. In this respect, Michael Pawlyn reclaims the words of the biomimetic expert Julian Vincent, who says that “in Nature shape is cheap, but material is expensive”, to explain that in architecture the opposite applies. The manufacture of complex forms is generally more expensive than the construction of simpler and more monolithic elements. However, the ongoing digital revolution could dramatically change that equation [70]. Here, 3D printing could play a determining role and biomimicry could be fundamental in this regard, since utilizing the full complexity allowed by additive manufacturing is the key to unlocking the huge potential of this technology for real world applications [71].

Another concept very widespread in Nature is related to material use, named “just enough”. Excess material in natural structures may incur in unnecessary energetic costs and additional load to its bearer. Through 3D simulation models, topology optimization methods have been applied successfully, with material placement being optimized based on simulation. For instance, more heavily loaded regions require a greater amount of material, rather than less heavily loaded regions. Then, repeated

cycles of simulation are carried out to find the optimal design, resulting in a structure with minimal material use but proper structural ability [72].

3D concrete printing already incorporates “green” concepts within their structures, not only bringing aesthetic but also structural and functional value. Thanks to the use of rounded corners and edges, there is a reduction in stress concentrations under loading conditions and in the amount of material required, when compared to an equivalent-strength straight wall. Despite opening up new opportunities related to the use of dome shapes, arches, rounded and organic support beams and cobwebbed structures, some manufacturing limitations related to overhang angles and material anisotropy still exist [72].

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Giving Shape and Functionality to the Matter: Digital Construction



Didier Lootens 

Abstract A fundamental modification of the construction is occurring with the adoption of processes digitalization. In the construction field, quality is often associated with cost, making the use of advanced materials not competitive with the most basic concrete. On the other hand, as the standard specifications increase with time to sustain safety issues or customer needs, construction has never been more complex. This complexity is nowadays highlighted by the multiplication of the layers, one for each request for thermic or acoustic insulation which makes the concrete part of the total cost less and less significant. In this environment, digital construction should not aim to replace precast elements but rather bring functionality to the matter, such as insulation, leading to a reduction in the trend of the addition of layers and therefore leading to a significant reduction of the cost. Moreover, the decrease in the total amount of material used will have a higher environmental impact than a substitution of concrete for so-called greener products. Currently limited by its cost when compared the traditional construction methods, the improvement of the technology from the robotic to the software will lead to a competitive technology for specific elements such as façade elements or structural columns. As the cost of 3D printed elements is independent of their complexity, as moulds are not required, digital construction allows architects to develop new ideas or to bring back brilliant ideas from past forgotten for economical reasons. To allow this revolution to occur, chemists, architects, engineers, and software developers must work together to overcome the challenges facing digital construction.

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1 Introduction

1.1 A Subsection Sample

For years, the construction industry has been unable to solve a series of challenges it is facing. The last major modification occurred more than 100 years ago with the use of reinforced concrete, changing the face of our cities. Historically, each industrial revolution has been requested by our need for life quality improvements, but not without environmental impact. The third revolution replaced a part of the manual work with the use of machines or robots, improving at the same time the productivity while decreasing the labor work intensity. It allowed the centralization and the globalization of the productions, reducing the number of the production facilities always larger, leading to an optimisation of the production cost and an improvement of sophisticated goods qualities. Currently, the economic model is based on a series of requirements which are: (i) cheap raw materials, (ii) cheap transport, and (iii) a constant economic growth. Without cheap raw materials, the optimization of the processes would not have a significant impact anymore, without cheap and fast transport, it would not make sense to produce on the other part of the planet and without constant growth, the mass production would collapse. Both the price of the raw materials and of the energy are then kept as low as possible, whereas the economy is pushed artificially to keep our growth constant, increasing state debts during the crisis. This system is then not sustainable, as both energies and raw materials are finite quantities, and the state debts reach barely acceptable limits. The construction industry is facing these issues and has not been optimized since the 60th [1]: a continuous decrease in its productivity is observed, mainly due to a lack of possible automation of the building processes. Unlike other industries, construction cannot be easily industrialized, due to building complexity and the material volume requested. The industrialization of the car industry with extensive used of robotics brought the industry to the level 3.0 whereas the on-site construction field kept a huge part of manual work as shown in the right picture of Fig. 1. Indeed, as the quantities of materials needed is enormous, the priority choice was always to keep the cost of the raw materials as low as possible while using a low degree of technicity



Fig. 1 Left: car construction line fully automatized, industry 3.0. Right: construction job site with extensive manual labour

of the materials. Concrete has then won a gold place in the cost optimization game: it is a cheap material, at about 10 c per kg, it is easy to prepare either on-site or in production, and only requires locally available materials such as sand, stones, clay and limestone, to be manufactured. The quantity used speaks of its success: more than 4 billion tons per year [1], the second most used material after water, and about 10 times more used than structural wood or brick. Reinforced concrete enables the building principle based on the slab-column connection which has not been changed for 100 years, as it is still considered to be the cheapest and fastest way of construction.

Within all these considerations, we could see that the current building process has reached its limits for more than 50 years, and only major modifications of its concept could improve its profitability. The age of robotics came in the 3rd industrial revolution, drastically improving the productivity of the automotive industry as shown in the left picture of Fig. 1. The same implementation has been made in the construction field with the concept of blocks assembly on site that has been produced beforehand in a precast or a wood factory for instance (Fig. 2), improving highly the organization of the building construction. Finished walls with windows and insulation, but also rooms such as bathrooms can then be installed as block to build a structure. The efficiency of the precast industry is proved by its annual growth of about 7% [2].

The first 3D printed house was made in the 1950th in the USA, the patented [3] processes are showing an extrusion of concrete which is deposed layer by layer with smooth surface as shown in the pictures of Fig. 3. Two persons could easily build a wall with a dry mortar mix, the top of the windows and doors are laid, and the sealing reinforcement is performed with liquid mortar. All the principles of 3D printing have

Fig. 2 Production of wood wall (Photo: courtesy of www.randek.com)



Fig. 3 The Urschel machine for building walls [3]



Fig. 4 3D printed houses with mortar or clay on site: Left: Constructions-3D, (Photo: courtesy of <https://www.constructions-3d.com>). Right: Wasp, 3D printed Gaia House, (Photo: courtesy of <https://www.3dwasp.com>).

been then invented for decades, but the technology has only been rediscovered and pushed forward the last 5 years.

Additive manufacturing using robots has been spread with the reduction of the machine cost and ease of use. Initially limited for prototyping and at a rather low scale, additive manufacturing is nowadays also used for large-scale projects. These days, hundreds of houses have been printed either on-site or with precast elements with different degrees of finishing and time executions as shown in the pictures of Fig. 4. The multiplication of the number of projects demonstrates the interest of using additive manufacturing in the construction field.

In this chapter, the history of the concrete used over time is reviewed in order to understand both the reasons in its success and its limitations and uses in modern constructions, understanding the evolutions which should inspire the new digital construction technologies. The resurgence of construction will come from its capacity to successfully combine the need for a decrease in the cost while improving quality and considering environmental impact. The new building principle, integrating new digital technologies including additive manufacturing, is then finally discussed and argued with examples.

2 The Use of the Concrete in Construction Over the Ages

Concrete and mortar are used massively for only 100 years, but the history of hydraulic binders is much older, starting at the age of the first civilizations. When a hydraulic binder is mixed with water and sand, we speak about a mortar, whereas when pieces of stones are added, we obtained a concrete. Hydraulic binders have been used to produce mortars to bind the stones of the pyramids by the Egyptian [4]. The Romans added pozzolan, pumice stone, or crushed terracotta to create the concrete which was used in the construction of the dome of the Rome Pantheon shown in the left picture of Fig. 5 [5]. In their fresh state, concrete and mortar behave like a liquid stone that can be modeled at the desired state before their constitutive hydraulic binders start hydrating to create a solid material. In the fresh state, concrete, or mortar



Fig. 5 From left to right: The Pantheon roof of Rome, Walter Gropius' Bauhaus Dessau Building, Museum of Civilizations of Europe and the Mediterranean (MUCEM, Marseille)

can be either poured, cast, sprayed, extruded [6], or now printed, to obtain the desired shape. This material is therefore perfectly adapted to bind stones, bricks, or to build walls or domes. Its use in antiquity was however limited as its production was more artisanal and possible with specific raw materials such as pozzolan, available in specific area only. Its use has not been spread even if its robustness has been proved with the existence of buildings still standing after more than thousand years without any cracks or damages. The binders used today in mortar and concrete have been rediscovered and industrialized in the nineteenth century; their mass production with simple and available raw materials such as clay limestone, and gypsum, allows to produce them almost everywhere at low cost. It took, however almost one century to witness the explosion of their use and the first applications of modern concrete were flowerpots, followed by boats [7]. The massive use of concrete for construction has been made possible with the combination of rebar, creating the reinforced concrete [8], as the combination of the high strength of concrete and ductility of steel was the solution to compensate for the low tensile strength and ductility of concrete. Reinforced concrete allows then to replace expensive cut stones and does not require the use of vaults, as reinforced concrete slabs can be directly supported by columns. This construction revolution, generalized by the Bauhaus movement at the beginning of the twentieth century [9], has dramatically changed the building principle as shown in the middle picture of Fig. 5. Concrete became adapted for the precast industry and the standardisation of the shapes led back in time to an enormous optimization of the construction cost. Concrete was then used for mass production of descent housing and was therefore affordable for everyone, but at the price of the standardisation and repetition of the forms.

There is not one concrete, a huge range is available, depending on the applications and the budgets. The construction started to keep apparent the concrete with the movement of the brutalism architecture in the 1950s [10], which is characterised by a minimalist structure showing the structural concrete with angular geometric shapes. This allows the increase of the construction efficiency at the price of monotonous colour and shape, starting the age of the modern concrete and its extensive use. Since then, construction productivity has never stopped decreasing, mainly due to the non-evolution of the construction principles, which required the use of large volume of concrete and an extensive labor force [11]. The productivity has decreased even further as the need for an improvement of the building standard rose; people

asked for better insulation, air quality, or acoustic. Those requested facilities have drastically complexified the apparent simplicity of the concrete façades, as it was not initially thought or designed to consider those needs. Reinforced concrete is only used for structural works, foundations, slabs, and walls, which should then be completed with multiple equipment or facilities such as roofing, heating system, air conditioning, escalators, elevators, sprinklers, electrical, insulate and weatherstrip, tiles, acoustical, toilets, sink and plumbing, paints. In the end, the total cost of the concrete in a building is now only representing less than 5% of the total cost. However, despite its low proportion of the building cost, the quality of the concrete foundations and structures has an important impact on their durability.

Concrete and mortar have an apparent simplicity of fabrication: mixing cement sand, aggregates, and some admixtures with water, and a more or less liquid mixture is obtained, which will then solidified in a series of chemical reactions, leading to a material similar to a stone. Concrete is then also called the “liquid stone”, but unlike natural stones, concrete results from a series of rapid chemical reactions which, if not well controlled, can lead to not durable material. Solid concrete is a porous material whose porosity is directly related to the amount of water used for its preparation. As water is needed for the fluidity of the concrete, it is often overdosed and consequently, the concrete porosity is not well controlled, leading most of the time to quick degradation. The simplicity of concrete and mortar preparation leads to a broad range of materials that will influence their properties, aestheticism, and durability. To guarantee those synthetic stones quality, a series of standards, norms and recommendations were created. However, it does not protect against human mistakes, weather conditions, or raw materials properties variations. A concrete cast on-site only needs to pass a series of limited and simplified quality controls, which are most of the time sufficient. However, the risk of durability is higher with reinforced concrete, as the rebar can react with salt and water, diffusing through the porous materials. This reaction leads to the rebar expansion and thus destroying all the structure. A growing number of collapsing buildings [12] and bridges [13] is observed when the concrete’s quality is not sufficient and/or when its porosity is too high. As comparison, the pantheon of Rome, built without rebar, lasted more than 2000 years as it is not concerned with steel corrosion.

Unlike stones which are stable for ages, concrete is generated from chemical reactions and can display a broad range of strength. Whereas concrete is the most used construction material, it suffers from some significant drawbacks: it has a relatively low tensile strength, can show possible issues with aggregates reactivity, it may also have aestheticism issues such as visible air bubbles and/or variations of colours, lixiviation, and of course cracks due to shrinkage and low flexibility. All these issues can be solved with the use of high-performance mortars, which have low porosity low porosity, high strength, no shrinkage or crack, no visible air voids, and important durability. However, because of their relatively high cost, about ten times more expensive than traditional concrete, their use is limited to repair applications or façade elements, such as for the MUCEM shown in the right picture of Fig. 5. For most applications, the cost and formulation complexity increases are not justified especially when concrete has only a structural application. The cost balance between

traditional concrete and high-performance mortar is changing with the implementation of additive manufacturing in the building construction. Indeed, the reduction of the labour cost with robotic construction as well as the possibility of using technical products in an industrial environment, could justify the higher cost of the materials. Therefore, the quality and durability of the concrete could be highly improved with the use of additive manufacturing but not at the cost of an increase of the price. With a higher optimization of the building process, it is now possible to use higher quality products, which allows using less of them, benefiting the ecological perspective.

3 Architectural and Ecological Considerations

As shown in the pictures of Fig. 6, houses can be built in mud, steel, and glass, plastic, prefabricated wood panels, clay, concrete bricks, or concrete panels. All these materials have advantages and drawbacks with a broad range of performances in terms



Fig. 6 Different building materials and technologies: Clay 3D printed with rice hulls insulation from **a** Wasp **b** glass **c** laminate panels (Hotel Charly's House) **d** wood **e** metal (Walt Disney Concert hall) **f** clay bricks **g** concrete blocks **h** concrete casted

of structural, acoustic, or insulation but also with different costs and ecological impacts. With the globally increasing ecological considerations, the use of traditional and locally available materials such as wood or mud for wall and even slab construction increases and is trendy. These materials have a green reputation, but one should consider all processes in calculating of the materials carbon footprint and avoid quick conclusions. Wood construction has been booming in the last few years, with the possibility to build large buildings with a calculated low carbon footprint [14]. Cut out of trees growing with photosynthesis; wooden boards can be considered as a material that holds up to 1.5 kg of CO₂ per kg. The equation used for wood construction is straightforward: each kilogram of wood stores about 1.5 kg of carbon dioxide. This equation works if the wood is used for construction; if burned, all the CO₂ stored is thus released. Also, prefabrication of wood houses is far from energy-free: it requires energy, transport and the intensive use of glues with a significant carbon footprint. We can estimate that wood construction produced about 0.3 kg of CO₂ per kg of material, far from being negative, and much more than concrete, which is around 0.1 kg of CO₂ for 1 kg of material. Wood is still a reservoir of carbon dioxide, but each construction should be considered in terms of its Life Cycle Assessment (LCA). At the end of the service use, all materials should be recycled or destroyed. In the case of wood, it ends up being burnt most of the time, releasing all the carbon dioxide in the atmosphere. The carbon balance of the wood construction, considering all its LCA, is then worse than concrete, which can, unlike wood, be easily recycled as aggregates after being crushed. The necessity of reducing our carbon generation should not precipitate us toward solutions that are less sustainable and more expensive. Considering that all foundations of wood houses should still be made in concrete, its carbon footprint is even more dramatic. The current fashion of wood construction is also leading to its global shortage and price increase [15], forcing the transport of the wood all around the world, and losing in the same time, its identity as a local and sustainable raw material. The idea of replacing concrete with clay or wood is also not sustainable.

Drastic modifications of the building principle should be done to both improve productivity and reduce ecological impact. As the third industrial revolution was based of the consumption rules with mass productions mainly abroad, the next industrial revolution should (i) be based on the use of local production using local raw materials, (ii) take into account Life Cycle Assessments considerations, and (iii) limit the amount of resources used during the construction.

Any construction required energy and materials, generating carbon responsible for global warming, and consuming our finite resources. All new construction should now be based on the zero-energy principle [16], which involves carbon-neutral construction and passive energy management. The establishment of carbon taxes have been made to motivate the industry to limit their carbon production. It could have an impact on their current economic model, and as calculating the total energy cost of a material is complex and can be easily twisted, it might not lead to a significant modification of the consumption of raw materials but rather to an optimization of numbers. Using alternative raw materials with minimal carbon content might not be the solution as concrete is already one of the materials requiring the least amount

of carbon and is easy to recycle when not combined with steel. The carbon balance of concrete is one of the smallest of all construction materials. The main issue stands in its overuse and consumption which should be reduced by (i) reducing trash and waste and integrating the LCA, (ii) reducing the total volume of material needed to build (iii) using as little energy as possible should be the goals in the future. As said Antoine de Saint-Exupéry, “Perfection is achieved, not when there is nothing more to add, but when there is nothing more to take away.” We are far from it in the construction field: each material uses only one functionality generating a combination of layers of materials which are most of the time glued. One layer per functionality: one for the structure, one for the acoustic, one for the insulation, one for the coating, and finally, a layer of paint. This sandwich structure is required to fulfill the specifications of the building in terms of structure, design, insulation of temperature, and noise. To the complexity of the multilayer wall and floor systems, we need to add the difficulty of recycling, because the different layers, well glued together, must be separated from each other. This sandwich structure is the outcome of the way of thought of making minor modifications instead of rethinking the whole process. While the digitalization of product manufacturing and services is changing how we work and interact, we should be able to integrate this revolution to the construction principles.

4 Digitalization of the Construction: New Building Concept

4.1 *Precast Versus On-Site*

Building construction is performed either on-site or pre-casted and assembled on site. Whereas all industries have been optimized for decades with intense robotization of manufacturing, construction has not changed much in the last 100 years, keeping a lot of tasks manual, mainly due to the size and weight of the structure built. The increase of the off-site building process with precast elements is taking a more significant proportion of the market. It can be explained by the possibility to control better the quality of finished products built in a controlled environment, but also by the ease of automatizing the construction of the building blocks or modular buildings with the use of robotics. Precast walls, with the integration of windows and insulation, can be installed on site in a few hours, whereas it would take months if directly made on-site (Fig. 7).

Digital manufacturing or 3D printing of concrete could be considered as an improvement of the construction technique and a step toward the digitalisation process. Simple calculation helps to check the current efficiency of onsite 3D printing. A house of 100 m² generates a wall surface of about 300 m², at a print speed of 10 cm/s with a layer height of 1 cm and thickness of 5 cm, we have a print weight of 300 kg per m² and a print distance of more than 100 km for a total weight of 90 t of ink requiring a total of 290 printing hours. 12 days and nights of print nonstop are needed for the structure of a 100 m² house. In comparison, concrete blocks are assembled

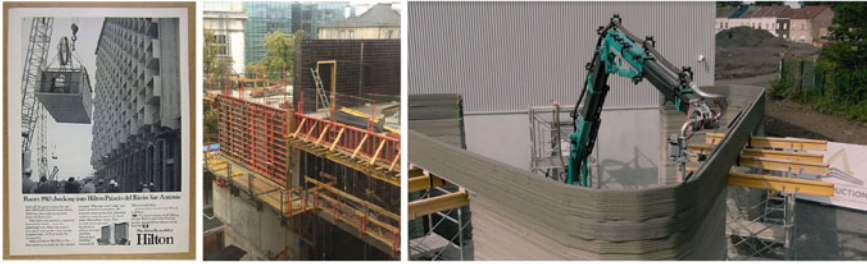


Fig. 7 Precast made in the 1950th, on-site construction made with formwork and 3D printed walls (Photo: courtesy of <https://www.constructions-3d.com>)

in three days by only two persons and are lighter, less than 200 kg per square meter. The on-site print speed should therefore be optimized by a factor ten to reach the same efficiency as hand brick layering. Considering that 3D print ink (the mortar used) contains two times more cement than conventional concrete bricks, we obtain a total carbon footprint of the wall three times higher for the print house than the classic one. A concrete brick structure costs about 3 k\$ of materials, whereas 90 t of inks with a competitive price of 200 \$/t would then give a cost of about 18 k\$ for the same structure, at the minimum six times more expensive from the raw material point of view. Taking into account that 3D printing can only be made for walls and not slabs, that the windows and door opening should be prepared with wood structures and that the final surface is most of the time not flat and/or irregular, the use of 3D printing on-site is, at the moment, far to be competitive. Moreover, on-site technic still requires much workforce with the addition of the cost for the printer installation. On the other hand, 3D printed on site still has an enormous improvement potential compared to traditional building technics. The resolution of the layers and the print speed could be improved. Concrete is a mortar with large aggregates, only allowing a large extrusion band, due to the size of the aggregates: if the maximum size is 2 cm then we need to print three times larger, so around 6 cm. The resolution increase can only be obtained with the reduction of the aggregate size: by limiting their size to 1 mm, for instance, we can obtain a resolution of 3 mm. It is then necessary to print mortar and not concrete to reach good printing resolution. The speed and acceleration of the printer are also critical to have a quick process: maximum speed is not really a problem, as a speed of 1 m/s can be reached easily by most machines, but speed conservation is a significant issue, limited by the high acceleration needed to obtain tight angles at high speed. Inconsistent speed, when not compensated by the ink's flow control, will generate printing irregularities.

4.2 *Digital Construction with BIM*

The digitalization of the construction starts with the organization of the processes: with the Building Information Modelling (BIM), it is now possible to digitally organize the plan and the building from its construction use and its destruction. The BIM is a digital repository containing all 3D structural and architectural information, integrating the fourth dimension with the time simulation of the construction schedule, the fifth dimension with the cost estimation, the sixth with the sustainability and energy analysis and the seventh for the life cycle and maintenance of the construction. It is a complete organizational tool to rationalize and optimize building construction. Complete use of the BIM on-site is complex as the processes request lots of different companies working in sequences: any delay generates disorganization of the workflow, resulting in a longer building process than estimated. The construction of a house should theoretically take two months, but it is likely to last more than six months due to the organization of the successive tasks. Implementing of the BIM with the on-site building principle is then difficult, knowing that each construction is a different trial resulting in various quality grades. In addition, it is more difficult to find trained and skilled labor for a tough job outside because of the weather conditions variation for the same indoor position. Once again, it leads to the conclusion that the implementation of the digitalization of the construction, similarly to car manufacturing, should be preferably performed with prefabrication and then simply assembled on site. Additive manufacturing would then be a way to improve the construction process, giving more possibility of shape due to the freedom of designs and the functionality of the printed matter.

5 Additive Manufacturing: Giving Shape and Functionality

Additive manufacturing in construction is not new: starting 100 years ago with slip forming, where a continuous vertical element of a given form is continuously cast using a short formwork moving upward with the pouring or compression process [16], and in the 1950th with the Urschel machine to build walls [3]. The 3D printing of concrete principles has not changed much since, with the superposition of concrete layers to build walls that can be straight or curved. The constitutive concrete ink used to be printed is simply formulated with a series admixture, mainly plasticizer, stabilizer, and accelerators, to be pumped and applied with limited sag. 3D printing of concrete is different from slip forming as it is applied with a robot, a gantry or a crane programmed to execute the request path [17]. Additive manufacturing objects are created with computer-aided -design (CAD) software or by 3D objects scanned used to generate the printed path generated in Gcode [18], which is then translated into the printer's language. The printer is depositing the material, layer by layer, to create lighter and stronger parts or entire systems. However, we barely observe this kind of optimization of weight and shape in construction, and the amount of material

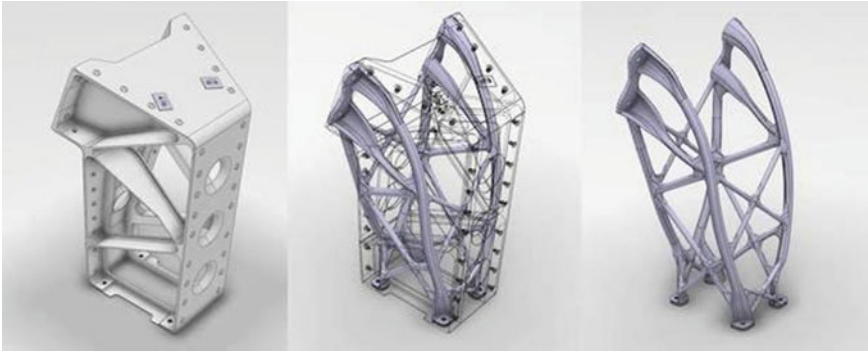


Fig. 8 Evolution of existing multi-part bracket to ALM concept for Eurostar spacecraft. (Photo courtesy of Airbus Defence and Space Ltd., Copyright Airbus Defence and Space Ltd 2015)

saved by giving optimized shapes is not significant when compared, for example, with steel additive manufacturing [19] as shown in Fig. 8.

Whereas additive manufacturing is generally known to optimize shapes, reducing both material use and waste, this optimization is not yet occurring in construction. We can observe round shapes with curved corners, but knowing that the optimization of building construction requires straight corners, the curved corners are far from practical. The degree of complexity obtained in 3D printing of concrete on-site is clearly not reaching the degree of perfection that can be achieved with 3D printing of metal or plastic and it is mainly due to the size of the structures, and the quantity of materials required. The resolution of 3D printing depends on the technology: on the large-scale range, we can use two different technologies: (i) extrusion-based or (ii) powder deposition [20]. While the powder deposition technology can reach high resolutions and allows impressive structures to be built [21], it is at the cost of a low printing speed and low strength, about 20 MPa [22, 23], and thus mainly due to the high porosity of the structure. The extrusion-based 3D printing has a lower resolution, but compression strength can reach up to 120 MPa with flexural strength up to 15 MPa. The extrusion-based 3D printing is then more suitable for construction whereas the powder deposition can be used for highly complex decorative shapes.

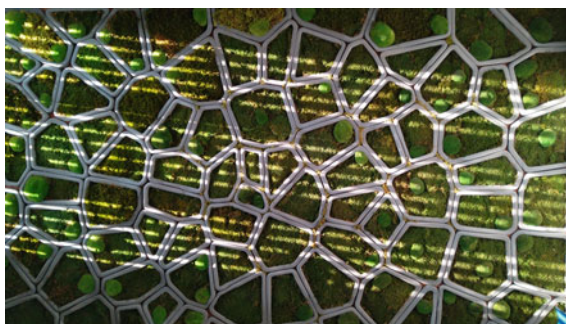
Additive manufacturing brings both (i) shape flexibility (ii) and new possibilities of functionality to the construction without needing a complex mold. Each design printed can be different without generating extra time to design it again, due to the parametrization of the design, allowing quick modifications by changing the numbers of some parameters. For instance, it is then possible to change the size and proportion of the structure without having to redesign all the objects. Objects made with additive manufacturing can also be generated directly from 3D scanned objects [24]. As an example, a bas-relief of the Ishtar gate (575BC, north side of the city of Babylon) was 3D scanned and printed. The Lion of Babylon was printed in 30 min with a size of 1.8 m bright and 1 m high with a total weight of 80 kg, as shown in the pictures of Fig. 9.



Fig. 9 The Lion of Babylon was made of glazed bricks from a portion of the Ishtar reconstructed in the Pergamon Museum in Berlin, Germany. **a** original Lion, **b** 3D scanned, **c** sliced for mortar print, **d** 3D printed with mortar

Generating such a mold would require much time and money compared to printed technology. This technic can be easily used for the generation of unique façade panels, which are currently expensive and then should be limited to a limited series of repetitive designs. Additive manufacturing is thus highly competitive to make a unique or small series of façades. The acoustic green wall shown in Fig. 10 is another example of a Façade element made with the combination of moss. This is an important topic, as concrete and glass are materials generating echo in a room, requiring acoustic improvement for the comfort of the people inside the room. There is a wide range of acoustic adsorber [25], and among them, we can find natural ones such as cork [26] and green walls [27]. Greenwalls are improving the interior microclimate, enhancing mental well-being, and regulating the room's dust, CO₂, and acoustic. In order to simplify the deposition of the green wall, 3D printed parts have been produced and glued on the wall in a Voronoi pattern [28], which has been, in that case, generated automatically. They are the grey elements in the picture of Fig. 10. It was easy to generate the pattern at the exact dimensions of the wall thanks

Fig. 10 Green acoustic wall fabricated with 40 pieces 3D printed mortar elements having a Voronoi pattern. The elements have been filled with different types of moss



to parametric strategies [29] and 3D printing. The wall is composed of 99 pieces, all different, giving a more artistic design without any further cost. All designs were printed in less than one hour, and the wall was successfully installed in eight hours by a non-specialist. Green elements have been easily inserted inside each printed element to bring acoustic comfort. In that example, thanks to 3D printing, a cost-effective design green wall could be quickly built.

Each industrial revolution or genuine innovation required a fundamental modification of the concept and, in our case of the building concept. The two main issues in construction are economical and environmental; in other words, the building is expensive, slow, and not ecologically friendly. Digital construction should help to improve these issues. The BIM can contain all the Digital information for the construction from its conception to its use; however, the production of the house elements is still not optimized, and we could build even more efficiently with the BIM. The on-site concrete construction is already efficient, and no further improvement could be brought with digital manufacturing as the structural concrete walls are replaced with the same structural walls but printed. The construction principle has to be fundamentally changed to integrate efficiently additive manufacturing. Seismic resistant structures such those built by the Egyptians or Inca (left picture of Fig. 11) with the ashlar masonry technic can now be produced quickly with 3D printing. The complex interlocking structure of dry-stone walls is resistant to earthquakes without needing mortar. The Quake column follows the techniques developed in ancient times [30], where each stone was interlocked with its neighbors to only allow a small displacement during an earthquake. It then avoids the wall's collapse which is observed when identical bricks are bonded with mortar. The weight of the original stones, a few tons, can be reduced dramatically by using additive manufacturing. Following this path, we designed a shelf, 3D printed with mortar with a wall thickness of only 2 cm. Fourteen pieces were printed in less than two hours with a total weight of 800 kg for a shelf of four meters in width and 2.5 m in height. The installation of the 40 pieces, shown in the right picture of Fig. 11, could be made smoothly by one person in two hours. As expected, the self-stability was improved due to the ashlar masonry technic, and no extra fixation between the elements were added.



Fig. 11 Left: Ashlar masonry build by the Inca. Right: shelf made with 40 pieces of 3D printed mortar

This principle can be easily generalized to all kinds of construction where the elements' inside could be filled with a lightweight material, keeping the structure light without needing mortar joints.

These examples demonstrate that complex shapes and objects can be 3D-printed with mortar to design structures combining several functionalities. The mortar is no longer limited to its structural function, as this technology can model it at a shape enabling extra properties, generating extra value. By doing so, each extra functionality will reduce the number of layers required, leading to a more straightforward recycling process and reducing the quantity of material used. The digitalization of the construction can use smart shapes to bring functionality to the materials which is no more limited to a single functionality.

Like reinforced concrete, which started with the conception of basic flowerpots, precast 3D printing of mortar also enables the fabrication of pots but with a much higher degree of complexity from the design point of view being either geometrical or organic. The size of the pots can be from tens of centimeters to a few meters, as shown in the pictures of Fig. 12, with a large panel of designs based on the principle of vase mode print which is a slicing method to continuously increase the height of the object during printing [31].

Using the same principle, it is possible to print various concrete furniture such as tables, window covers, sculptures, columns, or benches, as shown in the pictures of Figs. 13, 14 and 15. The only limitation is the imagination and creativity of the designer. It is also easy to quickly adapt the dimensions of a given design with its

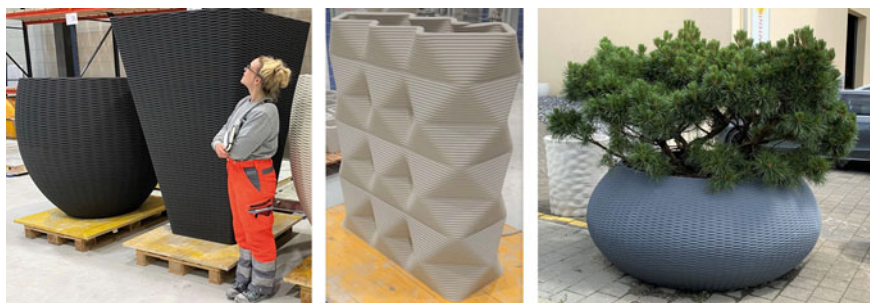


Fig. 12 Flowerpots and printed furniture produced at Affentranger Bau AG [28]



Fig. 13 Furniture made with 3D print mortar (right and left Affentranger Bau AG)



Fig. 14 Furniture made with 3D print mortar (Affentranger Bau AG)



Fig. 15 Reinforced columns and walls 3D printed (images from Affentranger Bau AG)

parametrization [32–34]. For instance, these parameters can control the object's size or shape. Thus, it allows customers to customize a design previously made by a third party by simply changing the values of those parameters. The technology is then available for everyone without special CAD competencies as customization is simply obtained by changing numbers.

Nevertheless, all these applications are niche markets which that do not involve the important volume of materials and can be seen more as a designer request than mass construction. Larger volume applications for precast 3D printing are obviously in the residential and commercial buildings. The complete construction of a house with 3D printing is facing a series of challenges: (i) cost, (ii) material properties, and (iii) building principle. The higher cost, already discussed, could be the main argument against 3D printing: the current technology is several times more expensive than traditional construction, mainly due to the material's high cost and the technology's productivity. It is then required to use less to have more: less materials used than the other building principles, while having higher productivity. 3D printing productivity for a building should be estimated using the number of square meters produced per hour rather than a volume or a mass printed per hour. The current productivity, rather low, can be estimated at about one m^2 printed per hour with a large with large among of concrete.

To become competitive in the wall market, the production rate should reach between 5 and 10 m²/h, with a maximum of 150 kg/m².

The material's properties and the building principle are the two other main challenges. On the material properties side, the mortar must be perfectly formulated. Indeed, we need a low viscosity mortar with a quick thixotropy and strength development, which reaches high final strength to have important durability and has no shrinkage during the entire curing period to avoid any cracks displaying high freeze resistance. On top of it, the binding between the printed layers must be perfect, and the overall quality of the print must be appealing. These parameters must be controlled to enable a consistent and robust printing experience. The number of successful 3D print concrete and mortar projects observed worldwide demonstrates that most of these issues are solved by good formulation specialists. The main issue is then not there, but rather is the fundamental properties of all cementitious materials: (i) they are brittle with close to no elasticity, (ii) their flexural strength is relatively low when compared to their compressive strength, and (iii) they have a thermal expansion; thus their volume is changing with temperature. More than limitations, these three remarks are intrinsic properties of cementitious and no scientist can solve issues only by tuning the mortar formulation!

For example, adding fibres can improve the flexion properties and increase the limit of elasticity, but not to the point where the materials can be used without any continuous reinforcement to print slabs or large elements which are not built-in vaults. The use of continuous reinforcement is then required for elements such as walls, columns, or slabs. The solution should be adapted to the situation and can be rather simple for some situations. For instance, columns can be simply reinforced with steel rebars and the printed column is thus used as mold for its reinforcement, as shown in the right picture of Fig. 15. To reinforce slabs, a similar solution is possible by smartly designing the slab to allow the addition of steel reinforcements. These applications are not complex but should be made with a high-performance mortar to avoid the corrosion of the reinforcement [36] as discussed previously.

Finally, it is known that concrete and mortar can expand or contract when temperatures respectively increase or decrease. Therefore, the shape of a cementitious object is not constant when temperature fluctuations occurs. The thermal expansion and contraction have to be taken into account, especially for very large structures. The coefficient of thermal expansion of concrete and mortar is in the range of 10 $\mu\text{m}/\text{m}/^\circ\text{C}$ [37], which means that we have a length change of about 1 cm for 50 m of concrete subjected to a temperature change of 20 $^\circ\text{C}$. It raises a problem for massive concrete structures, which are submitted to significant temperature differences between two of their surfaces, such as walls that separate the interior and the exterior of a building, for example, which could lead to the potential creation of cracks. Most of the elements of a building are fixed to the slab and therefore not allowed to change dimension independently to the slab, consequently any temperature decrease would tend to restrain the concrete, creating internal stress that can lead to dramatic cracks. Thermal joints are therefore required to avoid this issue, and these are the reason why no concrete wall is longer than 10 m and why every slab is cut on the top to allow the addition of contraction joints. For the same reason, 3D printing elements are limited

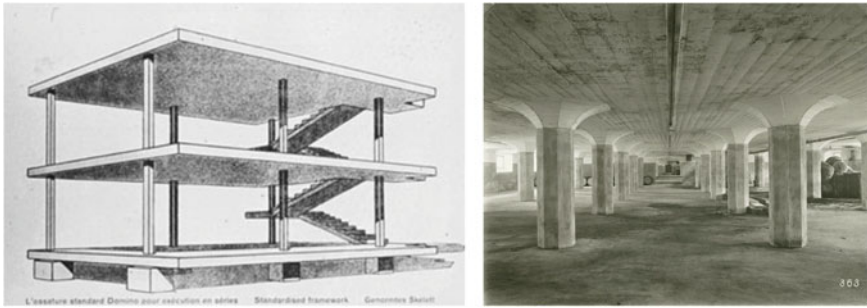


Fig. 16 Left: Dom-Ino house open floor plan, the modular structure designed by Le Corbusier (1914–1915). Right: Warehouse Giesshübel, built 1910; Zürich, Switzerland. In this building, R. Maillart applied the technique of the mushroom slab for the first time

up to a certain size, and no continuous house can be safely printed in one piece without having either shrinkage or thermal crack. It is required to print elements of a maximum size of 5–10 m length and connect them with flexible joints.

The building principle should be fully rethought with 3D printing, considering the advantages and limitations of the technologies and the materials without excluding the historical evolution of the construction. Most of the modern constructions are based on the principle of column slab connections initiated with the concept of the Domino House of Le Corbusier shown in the left picture of Fig. 16 [38]. The concept has been spread quickly and widely for the housing market due to both its low cost and its simplicity. The bound efficiency between the columns and the slab can be improved by optimizing the shape of the column. In the case a flat concrete slab, the load is directly transmitted to the columns due to the absence of panels or beams which has several advantages such as reducing both the height needed for the floor and the overall volume of the building. It leads to a reduction in the total weight and quantity of material needed. However, the transmission of the shear stress from the slab to the columns is problematic and thus requires a specific design of the column either with the shape of a “mushroom” or umbrella which are built from complex and expensive formworks. The systems appeared at the beginning of the twentieth century with the building designed by George M. Hill, followed by Turner [39] in the US and Robert Maillart in Switzerland [40] as shown in the right picture of Fig. 16. The major advantage of the flat slab was overshadowed by the cost of the formwork and the labour needed. These are why the mushroom and umbrella structures are limited to architectural structures such as pavilions, airports, or train stations and are not used to construct commercial or residential buildings.

In the age of Digital construction, expensive wood formwork can be replaced with 3D printed lost forms made with high-performance mortar. Double curves surfaces can be easily designed and printed in a few minutes with adequate printing technology such as used in Affentranger Bau AG [42]. The company renewed the use of mushroom structure with columns as represented in the pictures of Fig. 17. The columns of 300 kg are printed upside down with an angle of 40° , allowing an increase of



Fig. 17 Mushroom column printed at Affentranger Bau AG. The columns are printed upside down, transported, and later installed on the job site

the contact surface of a factor approx. 3.5 to optimize the link between the columns and the slabs. Classical construction technic has been used, where a C30/37 [43] concrete has been used to fill the columns. The technology has many advantages such as allowing a significant reduction of the rebar, the printed formworks is also an excellent protection of the steel and gives higher pressure resistance due to its high mechanical performances.

As a simple example we took the Affentranger Bau AG mushroom-columns for an underground garage built for Raumschneiderei GmbH. The profits of this kind of columns can be calculated with the pre-dimensioning of the concrete slab. The first main effect searched is to reduce the effective shear loads around the support leading to the reduction of both the quantity of steel and of the building time needed. Since the application of shear reinforcement is—according to the method used—often very laborious to prepare, especially by the cheapest way with stirrup reinforcement. The use of double-headed bolts are especially bringing beneficial in the mushroom columns for the punching shear [44].

In this case, following the Eurocode 1 [45], a 30 cm high slab has been designed with a load of 7.5 kN/m^2 , a dead load of 2 kN/m^2 including Flooring, covering, other equipment, and finally 5 kN/m^2 for variable loads are required and only working with static loads and not dynamical loads including wind, earthquake, or snow which would increase the quantity of steel. This gives us a static design load with safety factors equal to about 2 t/m^2 . In the first case, we are calculating the effective shear load in the slab for a 30 cm square column. After smearing the quantity around the column, calculations give us a quantity of $15 \text{ cm}^2/\text{m}$ stirrup shear reinforcement 0.3 m around the column as shown in the Fig. 18: 16 stirrups are needed for a final quantity of steel from about 11.8 kg and a concrete volume equals 0.226 m^3 .

In the second case, for the same loads and longitudinal reinforcement, we use the mushroom column design where no shear reinforcement is needed. Indeed, the shear resistance from the concrete and the Flexion steels are sufficient to resist the shear loads. In this case, the concrete volume corresponds to 0.286 m^3 . Steel mesh is needed to reinforce the inclined faces, corresponding to about 2 kg Steel for 1 m^2 . The price of the two structures have been compared on a basis of 900 €/T for the steel and 130 €/m³ for the concrete. Considering the price of the printed

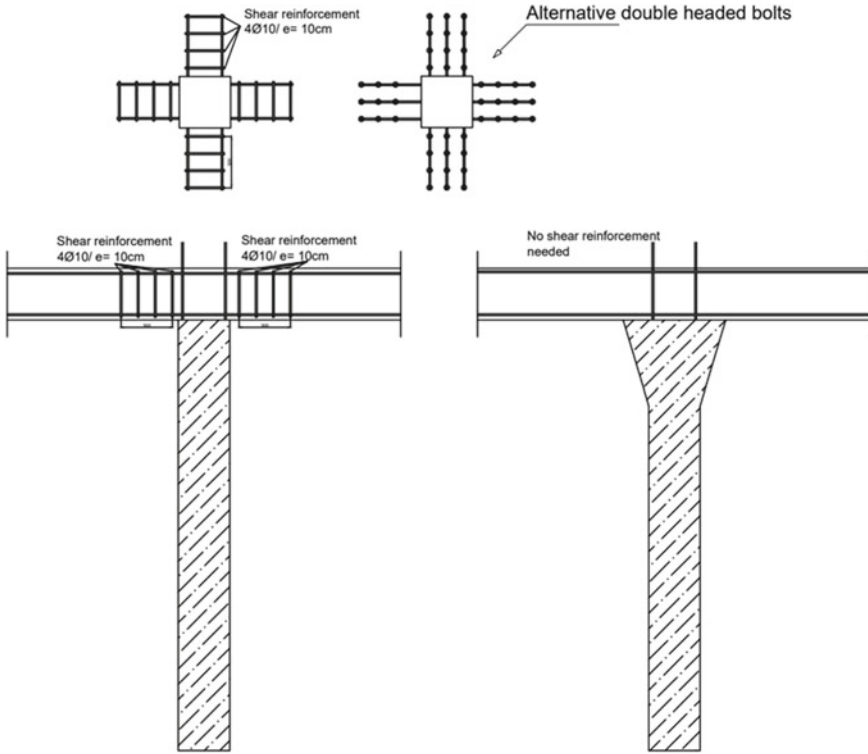


Fig. 18 Schematic representation of column slab designs. Left: straight column with shear reinforcement. Right: Mushroom column without reinforcement. The two upper draws are the top view of the two types of shear reinforcement structures

column of 800 €, the total cost of the 3D-Printed mushroom column is about 1.800 €, whereas the precast column cost 2.000 €. These prices are considering all parts of the columns constructions and can then directly compare the total cost of each technology. Taking into account the gain of design with 3D printing columns, we demonstrated that Digital construction could be already cheaper than a traditional one. In addition, the carbon footprint of the two designs has been compared, giving a consumption of 113 kg of carbon dioxide for the straight column design, compared with 84 kg for the 3D-printed mushroom column solution.

This last example illustrates how digital construction can be used to optimize cost and environmental impact, bringing back existing concepts and designs that have been forgotten or underused for economic reasons despite their architectural and structural advantages. Through this example, one can see how traditional construction and 3D printing technology can be combined to optimize the quantity of material used and reduce the total cost of the structure.

6 Conclusion

The construction field requires drastic modifications and improvements to face its long-term productivity crisis. The age of digital construction is coming with its advantages but also with a range of exciting challenges over a broad spectrum of fields: (i) economical, (ii) environmental, (iii) technical, and (iv) architectural. Their combination is needed to enable the transition, in the most conservative industry, from the “traditional” method to the digital method.

From the economic point of view, over the last 50 years, the construction industry has always been less profitable and productive compared to other industries, even if some optimizations have been continuously done regarding the cost reduction of the material. However, those optimizations are negligible compared to the constant addition of a broad range of normative regulations regarding insulation or environment for instance, leading to the increase of the costs. The current building principle has reached its limits, as the cost cannot be decreased anymore by previous methods. It should then be modernized within its concepts to improve its productivity drastically. Additive manufacturing construction should play a significant role in the resurgence of construction in many ways. First, with the democratization of the BIM use, to allow a better organization of the construction projects, but also with the use of additive manufacturing enabling new concepts and designs that were not possible before. Printing an entire structure is more expensive than its classical equivalent: technological and productivity improvements are thus needed to reduce the cost gap between them. The transition to digital construction can only be driven by economic improvements, a which would need both a low investment cost and high productivity. The development of small but efficient local precast 3D printing facilities would be required, mainly to reduce the transport cost for the large construction elements. A small 3D precast production can be run with only two persons with a limited initial investment compared to sizeable precast production. It also has the advantage of giving a payback in less than three years, encouraging the initial investment and thus allowing the spread of the new technology. Moreover, the precast conditions can guarantee a consistent production quality: on-site production cannot give any guarantees as the weather conditions, uncontrollable, have a huge impact on the material properties. Indeed, several material properties such as the setting time, the drying of the material, and the durability of the concrete or mortar are highly dependent on the temperature and humidity. The productivity and quality of the precast 3D printing mortar production should be then further improved with the control of those parameters. In the last 20 years, massive robotics improvements contributed to the technology implementation, from the decrease in cost to the increase in safety and performance. But in reality, the improvements on the slicing software, allowing more and more complexed design to be printed precisely and smoothly is the key factor from an architectural and structural points of view to push the technology even further.

The second main challenge is environmental, as construction should not only aim to reduce the carbon footprint of the materials used but, more importantly, reduce

the total quantity of construction materials needed. It is then needed to get more with less: a decrease in raw material consumption would both preserve our resources and reduce the energy used to treat and prepare them. In that case, additive manufacturing could play a major role, bringing the possibility to adapt the shape of the building block smartly, reducing the total amount of materials used. The use of higher material quality and its application with robots in a controlled environment enables the production of 3D printed objects with high and constant quality, improving the durability of the building while potentially reducing the cost of its life use. By giving shape to the matter, we enable the use of the material at its best: it is now used not only as a useless filler in construction but also as a way to bring additional properties with smart designs. When used sub-optimally, mortar or concrete generates additional weight to the structure for which a more robust structure is required, consuming even more materials. Optimizing the building structure is critical for decreasing its weight and lowering charge specifications. This is where Digital construction would bring the most.

As the third crucial point, the technology should be further improved, with the full integration of the BIM, but also with the use of more robust and durable materials both to limit their consumption and to give construction a longer life with a lower maintenance cost. As Digital Technologies combine robotics and materials, both should be improved in parallel as they interact. It can only be achieved with a strong collaboration between a broad spectrum of chemistry, process, robotics, and construction specialists. The current printing technology developed is also limited by the maximum acceleration of the robots and the limitation of the slicing software. Both should be improved to speed up the process further and decrease each element's printing time. Materials can and will be automatically further optimized, both from the performance and the cost points of view. More requirements would be done on the building principle: with the development of the block elements and modular buildings, the building construction organization will be even more straightforward. Finally, by combining design and material performance it is possible to compact different functionalities within a single 3D printed object.

Finally, the digital construction revolution will change how we design the building. As no mold is involved, the cost of a printed element is independent of its complexity, allowing architects more freedom to design elements. They can now consider their structural impact knowing that complexity does not add cost. They can now consider their structural impact knowing that complexity does not add cost. Taking inspiration from past construction is primordial, as most of the fantastic realizations made in the past are still standing. Former techniques were only abandoned for economic reasons despite their efficiency in design and static. The cost could therefore be transferred from the realization to the design of the element, which will completely change how we build. Ultimately, with the parametrization of the design, each design from an architect can lead to an almost infinite variation by simply modifying numbers independently of any anterior CAD knowledge. The parametrization of the designs is a way to increase the possibilities, improving the aestheticism without any additional cost, driving the building out of the repetition responsible of the city jungle, and giving everyone access to ecological and economical housing architectural designs.

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WASP in the Edge of 3D Printing



Massimo Moretti 

Abstract Magically attracted by the sparks of his father's grinder, Massimo Moretti grows up in the small mechanical laboratory at home and he delights in building works to aggregate his peers. He graduated in 1974 as an electronic technician and he started developing products. Massimo Moretti collaborates with Research Centers, Universities, R&D Departments, big national and international companies to create industrial automation projects, 3D modeling and prototyping not only in the field of mechanics but also in the interior design, cosmetics and chemistry fields. In his first 30 years of activity, he filed for about twenty patents before moving to open source and to the creative commons. His way of working is identified by invention and innovation. In his research path, essential for the product development, he has been approaching 3D printing since 2000. In 2012, together with a group of young designers, he founded WASP (World's Advanced Saving Project), a company that designs, produces and sells 3D printers Made in Italy all over the world. Massimo Moretti, taking inspiration from nature and from the observation of the Potter Wasp, which builds its own nest with material recovered from the surrounding environment, moves WASP to produce large 3D printers able to build houses with natural materials and available on the territory, at a cost tending to zero.

Keywords 3D printing · Raw earth · Crane system

1 Introduction

The revenue from the sale of 3D printers is invested in the research and development of integrated projects aiming to a production revolution that has the spread of prosperity as its main aim. Research that moves ahead hand in hand with eco-friendly, bio-materials and sustainable economic models. In order to spread knowledge and tools in an equal way Massimo Moretti takes education courses and increases research in the open source world.

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Fig. 1 Massimo Moretti © WASP



“Small slight thoughts take shape by depositing”

Massimo Moretti usually states; he invents, thanks to 3D printing, innovative solutions every day to meet the human needs: food, health, work, energy, art and culture (Fig. 1).

2 The Challenge of TECLA, a 3D Printed Global Habitat for Sustainable Living

Inspired by potter wasp, since 2012 WASP (World’s Advanced Saving Project) have been developing viable construction processes based on the principles of circular economy and digital fabrication. To reach the aim of the project, the research of WASP is divided in three separate fields: material providing, 3D printing technology and architectural design.

2.1 Selection of Materials and Their Use

To reduce the impact of the construction industry, WASP decided from the beginning to focus the research on the use of raw earth. If we imagine that today one-third of the global population is living in an earth-based house, we can immediately understand that the raw earth is a powerful construction material. Unfortunately, only a small percent of this population consider this a comfortable solution, mainly for two reasons: salubrity and the trend imposed by industrialization.

Due to these reasons, the aim of WASP is to develop a technology able to transform raw earth in a printable mortar and to use 3D printing to obtain construction integrated with the ecosystem and with a high living performance.

Starting with chemical and geological analysis of the local soil it is possible to formulate an accurate and customized mix-design in order to reach the necessary performance in terms of structural strength and printability.

At the base of the raw earth working process there is the extraction of the raw material, each time heterogeneous according to the mineralogical characteristics of the extraction soil. The collection process is followed by a dry filtering phase of the soil, with the use of a disc screen separator capable of eliminating the presence of stones larger than 10 mm, thus creating a grading curve in accord with the mix design. Thanks to this and the addition of natural fibers and binders (NHL) according to the mix-design, it is possible to have a printable mortar based on 95% of local raw material.

The latter is carried out through the use of the wet pan mill, a rotating kneading machine, with the addition of water. Mixing with a muller allows you to make a homogeneous and well-kneaded mixture effectively and quickly. Once the mixture is completed, the earth mixture is conveyed through continuous pumping systems to the extruder inlet with constant flow and pressure regulation through specific sensors. Depositing materials in useful forms to obtain the best performance has the advantage of being able to easily place the material where to serve in the form and quantity suitable for obtaining the necessary performance. This helps in the use of natural materials which typically do not have the technical characteristics of advanced concrete mortars. We look for the materials closest to the construction site. Typically the raw earth is the material present on the whole planet, but when we say the raw earth we are actually talking about a complex material composed of many components. The main ones are the materials found on the surface, like roots or decomposing materials or twigs and leaves, which go under the name of silt. This whole part is removed because it is not useful for the construction. Then, going deeper, we find the clay which is the basic glue for our mix and which is often found stratified with sands, pebbles and aggregates. The process involves the separation of clay and aggregate with a maximum grain size of 8 mm. We are looking for a natural fiber present in the area. The husk and rice straw are excellent materials because rice is a plant that lives in water and is designed by mother earth not to rot. It is so full of minerals that if we burn the rice straw we will obtain an ash in a rate of 70%. It is basically an organic mineral. Each fiber found in the area can be used such as wheat straw, coconut, banana ... each fiber, however, must be properly prepared to be mixed with clay and aggregate. Finally, a correction of the material is needed, in some cases there is too much clay, in others there is too much inert, with a small help of 5% of lime can significantly increase the quality of the mortar.

In this way, depending on the shape and performance we expect from a material, we can correct it and deposit it in the appropriate point and quantity.

Using pre-mixed is always possible but is not part of our research although our machines could more easily print them (Figs. 2, 3 and 4).

Fig. 2 Building
construction © WASP



Fig. 3 Building
construction © WASP



Fig. 4 Building team ©
WASP



Fig. 5 Crane system © WASP



2.2 Crane System

Since 2016, WASP has been working on the WASP Crane system in order to produce 3D-printed houses in the shortest possible time and in the most sustainable way.

Crane WASP is the world's first modular and multilevel 3D printer designed to collaboratively build singular and even more extensive architectural works.

The system is configured according to project needs and defines the structure of a safe and extremely efficient construction site. Each printer unit has a printing area of 50 m² and therefore makes it possible to build independent living modules with consistent shaping freedom.

For the first time, multiple printing arms have been synchronized inside a construction site like in an industrial production line. Thanks to a software synthesis of years of research in WASP, the system is capable of optimizing movements, avoiding collisions and ensuring simultaneous operation.

The redundancy of the system allows a consistent reduction of the printing time and the possibility of operating ordinary maintenance during the printing (Fig. 5).

2.3 TECLA

TECLA is a prototype of sustainable habitat developed by WASP and Mario Cucinella Architects to show the potential of the 3D printing technology applied on the earthen based architecture. It is the demonstration that 3D technology is able to create buildings by optimizing the construction process and minimizing the use of human and energy resources. The double dome solution made it possible to cover at the same time the roles of structure, roof and external cladding, making the house high-performance on all aspects.

TECLA can be synthesized in: 200 h of printing, 7000 machine codes (G-code), 350 layers of 12 mm, 150 km of extrusion, 60 cubic meters of natural materials for an average consumption of less than 6 kW.

TECLA is a prototype of sustainable habitat developed by WASP and Mario Cucinella Architects to show the potential of the 3D printing technology applied on the earthen based architecture. It is the demonstration that 3D technology is able to create buildings by optimizing the construction process and minimizing the use of human and energy resources. The innovative habitat model is a new circular model of housing entirely created with reusable and recyclable materials, sourced from local soil, carbon-neutral and adaptable to any climate and context. TECLA (which takes its name from Technology and Clay) was made in Massa Lombarda (Ravenna—Italy) with Crane WASP—WASP's brand new 3D printer in the construction sector—it represented a real challenge for 3D printing, maximizing the performance of a material among the oldest and at the same time among the most stimulating for the future of the green economy: the raw earth.

TECLA is in fact the peak of advanced research between matter and technology, it is the achievement of an unparalleled challenge that has brought the printing geometry to its physical limit. The project represents an unprecedented perspective for buildings and new settlements, in which the value of local raw materials is amplified by digital design. The double dome solution made it possible to cover at the same time the roles of structure, roof and external cladding, making the house high-performance on all aspects. TECLA can be synthesized in: 200 h of printing, 7000 machine codes (G-code), 350 layers of 12 mm, 150 km of extrusion, 60 cubic meters of natural materials for an average consumption of less than 6 kW. TECLA will be the first house to be entirely 3D printed using locally sourced clay. A biodegradable and recyclable 'km 0 natural' material which will effectively make the building zero-waste.

It will be built to adapt to multiple environments, and it will be suitable for self-production through the use of WASP's innovative Maker Economy Starter Kit.

This approach will limit industrial waste and offer a unique sustainable model that will boost the national and local economy, improving the wellbeing of communities. Furthermore, the scheme will significantly accelerate the construction process as the 3D printer will produce the entire structure at once (Figs. 6, 7, 8, 9, 10, 11 and 12).

“WASP takes inspiration from the potter wasp. We build 3D printed houses using earth found on the spot, under a sustainable perspective. The oldest material and a state of the art technology merge to give new hope to the world. GAIA, our first 3D printed house made with raw earth, was born a year ago. Today with our partners we are printing TECLA an entire eco-sustainable habitat. The planet is asking for a joint project that we share with Mario Cucinella”.

Fig. 6 Massimo Moretti and Mario Cucinella TECLA 3D printed house WASP + MCA © WASP



Fig. 7 TECLA house © MCA Mario Cucinella Architects



Fig. 8 TECLA house entrance © MCA Mario Cucinella Architects



Fig. 9 TECLA house aerial view © MCA Mario Cucinella Architects



Fig. 10 TECLA house interior view © MCA Mario Cucinella Architects



Fig. 11 TECLA house
interior view © MCA Mario
Cucinella Architects



Fig. 12 TECLA house
interior view © MCA Mario
Cucinella Architects



Architectonic Cement-Based Composites 3D Printing



Ana Mafalda Matos , Mehmet Emiroğlu , Serkan Subasi ,
Muhammed Marasli , Ana Sofia Guimrães , and João Delgado 

Abstract Additive manufacturing (AM) is a core technology on the paradigm shift to Industry 4.0 and has already impacted health, aerospace, automobile, military, fashion fields, and, more recently, construction. The most widespread AM method in the construction industry is 3D cementitious material printing (3DPCC). The main advantage is the freeform architectural design without formworks needed. Increased productivity, reduced costs, more safety worksites are potentially expected, and environmental benefits within materials savings and waste generation reduction. The freeform architecture and precision material placement make 3D printing particularly exciting for architectonic purposes, such as structures, buildings or elements. From the perspective of materials science, 3DPCC mix-proportioning remains one of the most critical aspects due to (i) the very demanding requirements, namely at fresh state; (ii) the needing of several constituent materials; (iii) the sensitivity of the mixtures to natural variations. The current work aims to add insight into the mixture design and assessment of architectonic 3PPCC through cooperation between science and industry. Employing locally available materials, establishing a rational basis for preparing and designing 3DPCC, applying novel testing procedures, providing understandings, and certifying its behaviour are fundamental questions. Thus a mix compositions study was accomplished, using locally available materials in Turkey, namely, white Portland cement and metakaolin. A systematic choice of fresh state parameters and identification of their threshold values to achieve printable mixtures, such as flow table and Casagrande, was established. Afterwards, the optimal mixture was employed to print architectonic objects, and additional tests were performed on samples. This work aimed to contribute to 3D printing as a way for the

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paradigm shift to Industry 4.0 and stimulate the adoption of clean and environmentally sound technologies and industrial processes in the Construction Sector. Besides, a straight collaboration among the scientific community and industry is essential to make 3D printing a more practical, cost-effective, eco-efficient and widely accepted technology.

Keywords 3D printing · Additive manufacturing · Mixture design · Architectonic cement-based composites

Abbreviations

3DPCC	3D printable cement-based composites
3DP	3D printing
AC	Alternated current
AM	Additive manufacturing
FA	Fly ash
h	Hours
HR	Relative Humidity (%)
LF	Limestone filler
LOI	Loss on ignition (%)
HPMC	Hydroxypropyl methylcellulose
MTK	Metakaolin
OPC	Ordinary Portland cement
SCM	Supplementary cementitious materials
SF	Silica fume
SP	Superplasticizer
w/c	Water to cement weight ratio
w/b	Water to binder weight ratio
PSD	Particle size distribution
HPMC	Hydroxyethyl methylcellulose

1 Introduction

Civil Engineering plays a crucial role towards a more innovative, sustainable and inclusive society, which are essential pillars of the 2030 Agenda Sustainable Development Goals (SDG). Additive manufacturing (AM) is a core technology on the Construction paradigm shift and has already impacted health, aerospace, automobile, military, fashion fields. The most widespread AM method in the construction industry is three-dimensional printing (3DP) of cementitious material. The main

advantage is the freeform architectural design without formworks needed. Additionally expected advantages are a faster production, an increased resource-use efficiency and adoption of clean and environmentally sound technologies and industrial processes, an improving competitiveness along the value chain. The carbon footprint left by 3DP may be reduced compared with traditional construction techniques, namely, due to: (i) less material used since there is no requirement for moulding and casting operations, avoiding common overorder concrete, (ii) highly-optimised construction processes and components that naturally reduce the amount of material used, (iii) significant diminution of carbon emissions related for the most part to transport since less traffic occurs as a result of limited labour requirements and workers. Improving worksite safety and creating high-end technology-based jobs and less risky are also expected [1–4].

The two main approaches on 3DP of cement-based composites (3DPCC) are the extrusion-based method and the powder-based method [5, 6]. The extrusion of 3DPCC requires very demanding engineering properties, namely in the fresh state, where pumpability, extrudability and buildability should co-exist. Thus, the mixture design needs to accomplish those requirements. The aggregate content of 3DPCC mixture is significantly reduced, usually in a mass ratio below 1, compared to cement content. The increased amount of very fine powder materials in the mix design [7], which may achieve 70% of the volume [8], is fulfilled with extra dosages of cement and SCM. Most common SCM employed in the concrete industry are silica fume (SF), fly ash (FA), slag and limestone filler (LF). However, many limitations may appear by using the common SCM as the main ingredients of 3DPCC if a long term application is considered. The main problem for silica fume and slag is the limited quantity of their production worldwide [9, 10]. Besides, SF may be expensive. Even though FA availability is relatively higher, more than one third is not suitable for blending with cement due to quality reasons [9, 11]. PC with LF is widely used in European countries namely because it has technical benefits on some cement-based materials properties such as workability, density, compactness and permeability, capillarity, exudation and cracking risk reduction. Fillers can improve the hydration of Portland cement as they act as nucleation centres. In fact, it was observed that LF additions up to around 5% can react with cement and enhance most properties [12–14]. However, using the above 10% of limestone alone as the substitution of PC in the binder fraction may result in higher porosity and reduce the mechanical strength [10, 12].

Consequently, alternative sources of SCM, such as calcined clays, are of interest. Kaolinitic clays are widely available in the earth's crust. A heat treatment between 600 and 800 °C of such clays leads to the dehydroxylation of the crystalline structure of kaolinite to give metakaolin [12, 15]. Metakaolin (MTK) or high grades of calcined kaolinitic clay with high purity are generally used by other industries, such as paper, ceramics, and refractory [10]. It appears to be an economical choice in the concrete industry to use lower grades of calcined clay, which are widely available compared to MTK. However, the calcined clay sourced from different suppliers may contain various percentages of MTK [8]. Different calcined clay may have different compositions, secondary phases, fineness, and specific surfaces [16], which will

influence the rheological behaviours of fresh cementitious materials, such as 3DPCC. During cement hydration, the metakaolin phase reacts with portlandite, water and/or sulphates to form C-A-S-H, ettringite, AFm-monosulfoaluminate [14]. When clinker is substituted by a combination of calcined clay and limestone, the limestone can react with the additional aluminate provided by the metakaolin and portlandite to form AFm-carboaluminates [16]. Antoni et al. [15] showed that the combined formation of extra C-A-S-H, ettringite and carboaluminates in the pozzolanic reaction leads to a refinement of the microporosity and an increase in compressive strength [10]. Damidot et al. have also shown [17] that the increase in solid volume in a ternary blend cement-limestone-pozzolan when replacing limestone with pozzolan can be related to the reactive aluminous content of the pozzolan. In this sense, the use of metakaolin is interesting because of its high reactive aluminate content.

1.1 Research Significance

Technological development for 3D printing as a breakthrough construction method increasingly involves cooperation both nationally and internationally, not just between disciplines, but with other research centres, teaching institutions, and industry.

Fibrobeton is a precast concrete industry located in Turkey aiming to raise the living standards of all people by adding strength, aesthetics and spirit to buildings and to add value to the common cultural heritage that future generations will enjoy [18]. Two examples of Fibrobeton facade buildings are presented in Fig. 1.

The freeform architecture and precision material placement make 3D printing particularly exciting when architectonic issues, such as complex or high variable geometries, which require heavy effort on mould project and production. Besides, those moulds are sometimes used a few times, giving rise to economic losses and creating environmental concerns. 3DP can also be competitive compared to subtractive manufacturing since fewer materials are wasted, and cost savings are also expected.

White cement formulations are popular due to colour requirements for architectural purposes. White Portland cement is characterised by lower Fe_2O_3 and alkalis contents and higher free lime content than grey cements. Because a higher fineness of cement increases the brightness of white colour, it is usually ground finer than grey Portland cement. This contributes to achieving a rapid setting and higher early compressive strength, meeting the requirements of EN 197-1 [19]. Compared with ordinary (grey) cement, these common differences in white Portland cement should not adversely affect the final concrete performance, thus requiring a proper selection and combination of constituent materials at the mix-design stage. In that context, partial replacement of white Portland cement by a pozzolanic material, with white colour such as metakaolin, can be beneficial considering economic, technical and environmental aspects.



Fig. 1 Example of fibrobeton façade buildings: **a** Art Museum (İstanbul) and **b** Cher Hotel (Istanbul)

1.2 Research Objectives

The successful design of a white 3D printable cement-based composites architectonic purposes depends mostly on understanding the influence of raw material and mix-design parameters on workability, visco-elastic and mechanical properties.

The present study aimed to design 3DPCC for architectonic facade building applications. Based on the findings of previous research and knowledge of the authors, a binary mixture of white type II Portland cement and MTK were selected to produce white printable architectonic cement-based composites. A white type II Portland cement was preferred because of the colour requirements and is widely available in Turkey and most European countries. Type II cement, including LF, is recognised for improving workability and can contribute to temperature control rise avoiding thermal shrinkage cracking. A commercially available MTK was included to enhance cement-based composites' printability behaviour and durability. Besides, MTK type was selected based on its colour (white).

Within a mixture compositions study, the best combination of powder materials, water/binder ratio and superplasticiser dosage was achieved, minimising plastic shrinkage deformations while maintaining printability. Afterwards, scale-up proceeded by production 30 L for printing predefined objects.

2 Materials and Methods

2.1 Raw Materials Characterisation

3D printable cement composites were produced using a binary blend of cement (CEM II/B-L 42.5 R, according to EN 197-1) and metakaolin, both commercially available in Turkey. The relevant chemical and physical properties of fine powder materials are summarised in Table 1.

The aggregate fraction was a natural siliceous sand with a maximum diameter of 0.3 mm and 2650 kg/m³. The silica sand was obtained from Celiktas Industry and Trade. Inc. is classified as AFS 80-90. Particle size distribution (PSD) of silica sand, cement and metakaolin are depicted in Fig. 2, in which PSD of cementitious materials was determined by laser method and PSD of aggregate by sieving.

Polycarboxylate-based superplasticiser (SP) and hydroxyethyl methylcellulose (HPMC) were used as admixtures, and the main characteristics are summarised in Table 2. Tap water was used.

2.2 Mixture Compositions Study

The first challenge of the study was to design a printable mixture composition with local raw materials selected. This is a fundamental aspect and is an innovative material with very few studies in the literature to date using non-property mixtures. Thus, based on the bibliographic research [6, 8, 20] and previous knowledge of the authors on mix design of cement-based composites [21–25], an iterative study of composition was performed to obtain a mixture presenting pumpability, extrudability and buildability.

In brief, after each mixture batch manufacture, fresh states properties were evaluated, namely, workability, Casagrande and a manual printing test. Afterwards, prismatic specimens were cast for each mixture, and electrical resistivity and mechanical strength were assessed. The experimental programme is summarised in Table 3, and the following sections describe in more detail each test procedure. After founding the optimal printable mixture, 3D printing through a CNC machine was performed (Sect. 3).

Table 1 Main oxide composition, LOI and physical properties of cement, LF and MTK materials

	Properties	Cement	MTK
Main oxide composition (%)	SiO ₂	17.50	62.27
	CaO	63.50	6.88
	Fe ₂ O ₃	0.21	0.3
	Na ₂ O	0.25	0
	Al ₂ O ₃	3.30	15.72
	MgO	1.15	0.18
	K ₂ O	0.27	0.66
	TiO ₂	–	0.31
	P ₂ O ₅	–	0.06
	Cl	0.008	0.013
	SO ₃	2.80	1.29
	Free CaO	1.40	–
	Insoluble residue (%)	0.12	85
Physical properties	Density (kg/m ³)	3000	2600
	Specific surface (cm ² /g)	5500	9180
	Initial setting time (min)	120	–
	Final setting time (min)	145	–
	Volume stability (mm)	1	–
	Whiteness Y (%)	86.5	93.0
	Brightness L (%)	93	84
	Residue at 45 µm (%)	1.5	0.1
	Residue at 90 µm (%)	0.1	–
Mechanical properties	Rc, 2d (MPa)	28	–
	Rc, 7d (MPa)	49	–

2.3 Specimens Manufacture and Mixture Proportions

The mixtures were prepared in batches of 1.2 L using a two-speed mixer in accordance with EN 196-1. Table 4 presents the mixing procedure followed for 3DPCC preparation in the mixtures compositions study. After mixing, fresh state properties were assessed using the slump (EN 12350-5) and Casagrande test methods (EN ISO 17892-12), both described in Sect. 2.4. Three prismatic specimens (40 × 40 × 160 mm³) were moulded to assess electrical resistivity and compressive strength. After

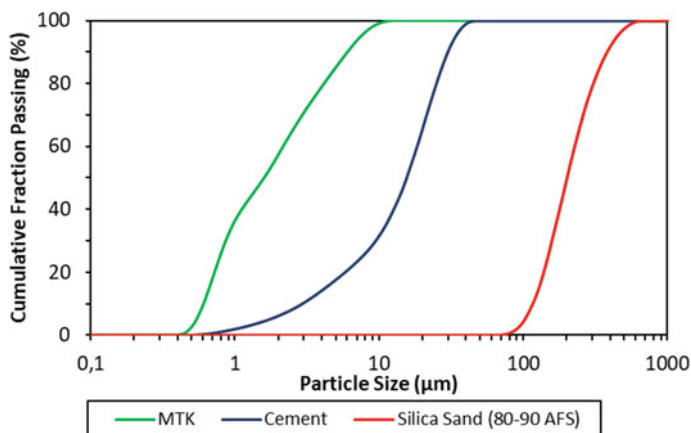


Fig. 2 Particle size distribution of cement, metakaolin and silica sand

Table 2 Main characteristics of the SP and HPMC

Polycarboxylate-based superplasticiser (SP)	
Color	Light brown
Density (g/cm ³)	1.13 ± 0.05
Chloride content (%)	<0.1
Alkali content (%)	<3.0
Solid content (%)	52.5
Water reducing rate (%)	<130
Hydroxyethyl methyl cellulose (HPMC)	
Appearance	Powder
Solubility	Water soluble
Viscosity (1), mPa s	9900
pH (2% solution)	Neutral
Moisture content, %, max	7.0
Polycarboxylate-based superplasticiser (SP)	

one day, the specimens were demoulded and kept in a fog chamber (under controlled temperature 20 ± 2 °C and HR >95%). For optimal printable mixture, additional tests were performed, namely, slump loss (described in Sect. 2.6). The mixtures proportions study is presented in Fig. 3.

Table 3 Experimental programme summary

	Property	Test standard or procedure	Testing age	Curing regime	Number of specimens for each testing age	Samples geometry
Fresh state tests	Workability (slump)	EN 12350-5 Section 2.4	After production	–	–	–
	Casagrande	Section 2.4	After production			
	Slump loss test (only for optimal mixture)	Section 2.5	After production, 5, 15 and 30 min			
	Manual printing test	Section 2.6	After production	–	–	–
Hardened state tests	Electrical resistivity	Section 2.7	1–7 days	20 °C, HR >95%	3	Prismatic 40 × 40 × 160 mm ³
	Mechanical strength	EN 196-1 Section 2.8	2 and 7 days		3	

Table 4 Mixing procedure sequence

Steps	Duration (s)	Speed
Add powder materials (sand + cement + MTK + 80% mixing water) and mix	120	62.5 rpm
Stop the mixing and scrape the materials on the sides and bottom of the bowl		–
Continue mixing	120	62.5 rpm
Stop the mixing and scrape the materials on the sides and bottom of the bowl		–
Add remaining water (20% mixing water) + 75% Sp and mix	120	62.5 rpm
Stop the mixing and scrape the materials on the sides and bottom of the bowl (if needed)		–
Add 25% Sp and continue mixing	60	125 rpm

2.4 Fresh State Tests

A motorised mortar flow table was used to measure the flow diameter of fresh mixes in accordance with EN 12350-5. For the slump flow test, the fresh composite was cast in two layers of brass cone, and each layer was tamped 10 times. After the surface smoothing process, the cone was removed. Then, by turning the mechanical arm, 15 free falls of the table were ensured. The slump flow values of two perpendicular spread flow diameters measurements were recorded, and the average value was considered.

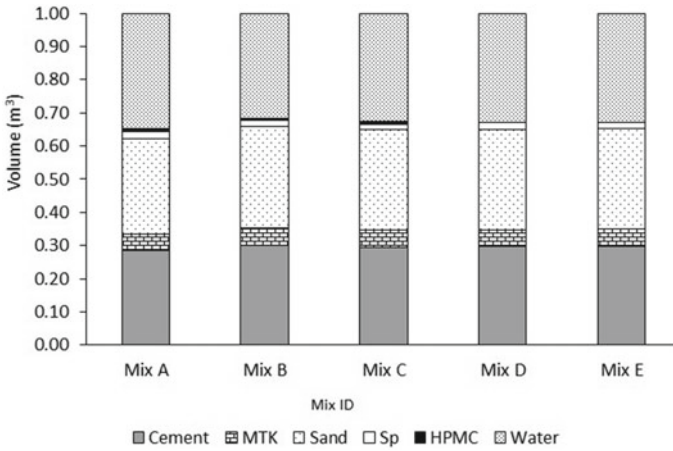


Fig. 3 Mix proportions study

To characterise the consistency of printable cementitious mixtures, the Casagrande test method, which is used in the classification of soils, was used in accordance with the EN ISO 17892-12. Approximately 30 g of fresh composite sample was placed on the Casagrande device with the help of a scraping tool. Afterwards, the composite surface was divided into two through a brass separator, and the manual arm was turned. The number of falls on the numerator was recorded when the separated mortar surface was closed by hitting the ground each cycle.

2.5 Slump Loss

The slump loss procedure was performed only in the optimal mixture to assess the workability loss by time and following the procedure described in Sect. 2.4. In brief, after the manufacturing slump was evaluated, then the sample was again put inside the batch and kept covered with a wet cloth. The slump was then measured after production, 5, 15 and 30 min, in which 0' was considered the time when water was added to cement. Before each measurement, the fresh composite was mixed for 1 min at a low speed.

2.6 Manual Printing Test

A manual printing procedure developed by the authors was performed to check the extrudability and buildability of the fresh mixtures quickly. This procedure consists of filling a plastic bag, in which an edge was cut previously (20 mm), and printing

Fig. 4 Manual printing test procedure



through manual pressure, as depicted in Fig. 4. The same person always performed the procedure.

2.7 *Electrical Resistivity*

Resistivity is an intrinsic property of the material that relates to the ability of concrete to carry an electric charge. It depends mainly on the hydration process (nature and topography of pore structure), changes in pore solution composition, moisture and temperature conditions. Electrical resistivity of water-saturated concrete provides indications on the pore connectivity and, therefore, on the concrete resistance to penetration of liquid or gas substances. Thus, resistivity is a parameter that accounts for the main key properties related to concrete durability [25, 26].

In the present work, electrical resistivity was assessed by the two electrodes technique [27] on prismatic specimens ($40 \times 40 \times 160 \text{ mm}^3$). The two-electrode method was used to determine the resistivity of the specimens under alternating current (AC). The resistivity was measured with two stainless steel plates pressed to opposing (mould) surfaces via wetted cloth.

A signal generator applied a sinusoidal current of 50 Hz frequency, and the response was recorded with the multimeter with 0.01 A resolution. Using Ohm's Law, as shown in Eq. (1), the relationship between the intensity of the applied current and the potential difference measured gives the material's electrical resistance. The resistivity is obtained by applying to the electrical resistance a geometric factor, which depends on the geometrical dimensions of the specimen and the electrodes used. The electrical resistivity measurements were performed on the samples until the 7th day of curing.

$$\rho = \frac{V \times A}{I \times L} (\Omega \cdot m) \tag{1}$$

where;
 ρ is resistivity ($\Omega \cdot m$), V is voltage (V), A is cross-section area (m^2), I is electrical current (A), and L is the distance between electrodes (m).

2.8 Mechanical Strength

Three prismatic specimens ($40 \times 40 \times 160\text{ mm}^3$) were produced to assess three-point flexure and compressive strengths according to EN 196-1. As mentioned in Sect. 2.2, specimens were cured in a fog room (under controlled temperature $20 \pm 2\text{ }^\circ\text{C}$ and HR > 95%) and removed to perform the mechanical test at established ages of 2 and 7 days. The pacing rate of loading was $(50 \pm 10)\text{ N/s}$ and $2400 \pm 200\text{ N/s}$ for flexural and compressive strength tests, respectively.

3 3D-Printing: Scale-Up

After establishing the optimal mixture considering results obtained from previous tests (Sects. 2.4–2.8), it followed the scale-up with the production of a volume of 30 L for 3D printing. The mixture proportions and main ratios are presented in Table 5. A pan-type mixer with a mixing capacity of 56 L, an operating speed of 70 rpm, and an operating speed of 1.5 kW were used to produce 30 L of the optimal mix. Firstly powder materials were added and dry mixed for 1 min. Afterwards, water and super-plasticiser were added while mixing. Slump tests were performed when the mixture was properly mixed and homogeneous, as described in Sect. 2.4. Besides, several prismatic specimens were cast for electrical resistivity and mechanical strength assessment (as described in Sects. 2.7 and 2.8, respectively). Test performed on samples

Table 5 Mixture proportions of the optimal mixture (Mixture E) for scale-up (0.03 m³)

	0.03 m ³
Cement (kg)	27.00
Metakaolin (kg)	4.05
Silica sand (kg)	21.66
Sp (kg)	0.36
Water (kg)	8.55
Main ratios	
w/c	0.324
SP/fines (%)	1.159%

Table 6 Experimental programme summary for scale-up

	Property	Test standard or procedure	Testing age	Curing regime	Number of specimens for each testing age	Samples geometry
Fresh state tests	Workability (slump)	EN 12350-5 Section 2.4	After production, after printing	—	—	—
	Casa Grande	Section 2.4	After production			
Hardened state tests	Electrical resistivity	Section 2.7	1–7 days	20°C, HR > 95%	3	Prismatic 40 × 40 × 160 mm ³
	Mechanical strength	EN 196-1 Section 2.8	2 and 7 days		3	

of the scale-up batch are presented in Table 6. After production, the fresh composite was transferred to a plastic container and transported to printing facilities.

A 110-L capacity 1.5 kW pump with a 396 rpm working speed and a 35-L/min pumping speed was preferred to supply the fresh composite to the CNC router. A servo motor industrial control unit with a torque of 12 Nm and a bridge-type 3-axis CNC router was used to prepare mortars. The working volume of the CNC was 4650 × 3125 × 1500 mm³. The printing set-up is shown in Fig. 5a. 3D models were designed with Rhinoceros and printings organised using the 3D Print slicing program prussaSlic3r, as depicted in Fig. 6. The product was printed from a 20 mm diameter steel nozzle (see Fig. 5b), with a minimum of 50 m/min in the X and Y axis and



a)



b)

Fig. 5 a Printing machine and b 20 mm nozzle

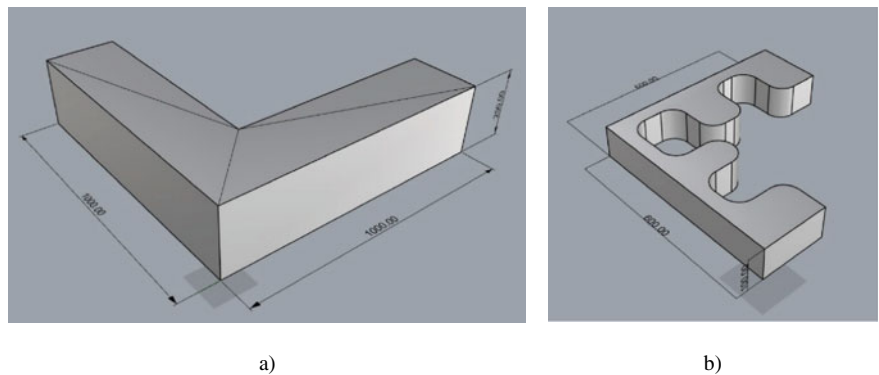


Fig. 6 CAD design for 3D printing: **a** “L” shape and **b** hexagonal shape

a maximum of 25 m/min on the Z-axis. After the printing process, the slump tests were performed as described in Sect. 2.4.

4 Results and Discussion

4.1 Mixture Compositions Study

As seen in Fig. 2, in Mix A, Mix B, and Mix C, the HPMC effect was evaluated in the mix proportions. However, HPMC was not preferred in mix D and Mix E proportions. In addition, water and SP dosage varied in the blends. The slump-flow test results are demonstrated in Figs. 7 and 8. As predicted, a reduction in flow diameter occurred

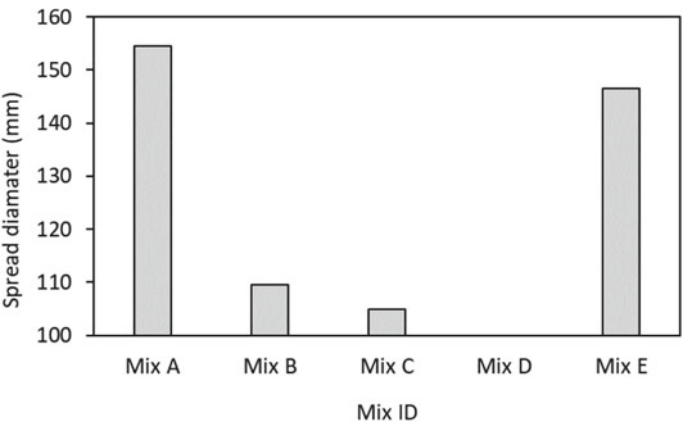
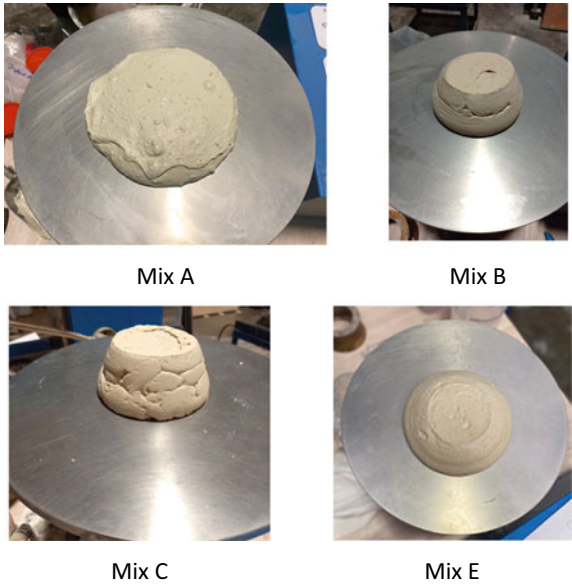


Fig. 7 Spread diameter test results

Fig. 8 Slump test



with the decrease in SP and water in Mix A, Mix B, and Mix C. In the mixtures without HPMC, namely aiming a lower cost and sustainable production, a dramatic increase in spread diameter was observed, Mix D, which is not suitable for printing performance, instead, it was self-compacting. Then, the SP dosage was reduced, and a 147 mm flow diameter was achieved in Mix E.

Casagrande test results are presented in Table 7. Casagrande test, which is used to determine the Atterberg limits of soils, was preferred in the study to assess the fresh state properties of printable mortars. As can be seen from the results, drop numbers are sensitive against the small changes in the mixture proportions. In addition, when the drop numbers and flow diameter values are evaluated in an integrated way, the test is not applicable in fluid consistencies, i.e., unsuitable for printing. When the results are examined, measurements of higher drops of more than 5 correspond to more suitable consistencies in terms of printability. However, it is thought that very high drop numbers may cause problems in terms of pumping performance. Here the

Table 7 Casagrande test results

Mix ID	Casagrande (number of drops)
Mix A	N.A.
Mix B	23
Mix C	36
Mix D	N.A.
Mix E	7



Fig. 9 Manual printing tests of mixtures produced

Mix B and Mix C, where the w/b ratio is low and HPMC was employed, the drop numbers were observed as high as 23 and 36, respectively.

Figure 9 depict the printability performance based on the manual printing test (developed by the authors and described in Sect. 2.6), which intended to measure the printability performance easily. As can be perceived, Mix A did not present buildability, even though it was easily extrudable and with no plastic shrinkage was observed, corroborating slump and Casagrande tests. Mix B and C presented printability and buildability but were very hard to extrude due to the fast setting. Mix D was self-compactable; thus, manual printing tests, similar to workability and Casagrande, were impossible to perform. Mix E presented printable behaviour and is not hard to extrude and buildable.

Flexural and compressive strength results are depicted in Figs. 10 and 11, respectively, and it also includes Mix E Print, which corresponds to 3D print scale-up mixture. The strength behaviour was not the main focus of the current work, instead, authors were interested in printability performance. However, the mixture achieved high compressive strength values, between 27–60 MPa at 2 days and 55–87 MPa at 7 days. Between 2 and 7 days, a significant evolution of compressive strength was

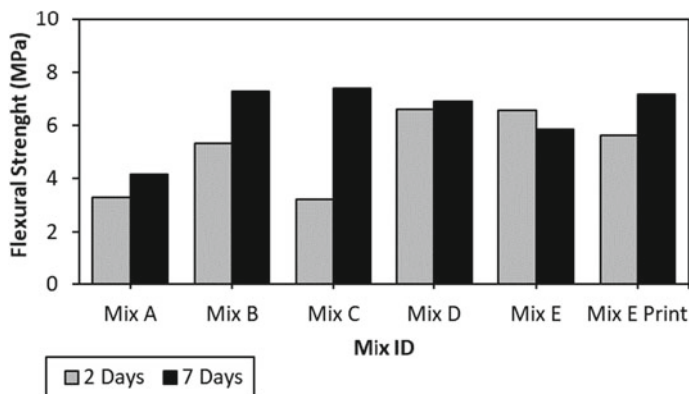


Fig. 10 Flexure strength test results

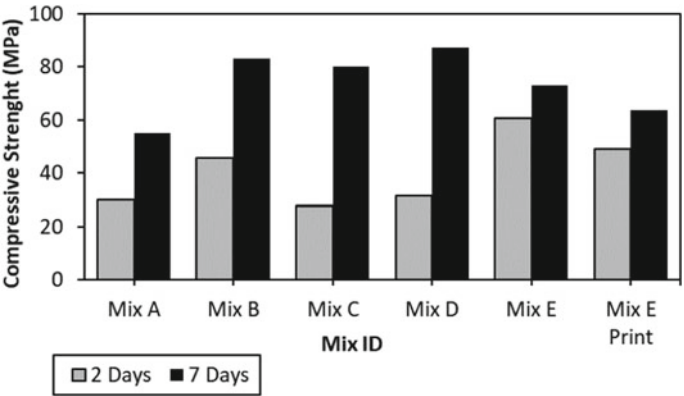


Fig. 11 Compressive strength test results

observed for all mixtures studied, which is common when very active SCM, such as MTK are employed [10, 14, 15]. As expected, Mix A presented the lowest strength due to higher water content. Even though Mix B presented the lowest water content, it was hard to cast and compact, which might have impacted mechanical behaviour. Mix E achieved 60 MPa at 2 days and 73 MPa at 7 days. Mix E print resulted in slightly lower compressive strength at 2 and 7 days than Mix E, which is common in scale-up processes, where more variables exist.

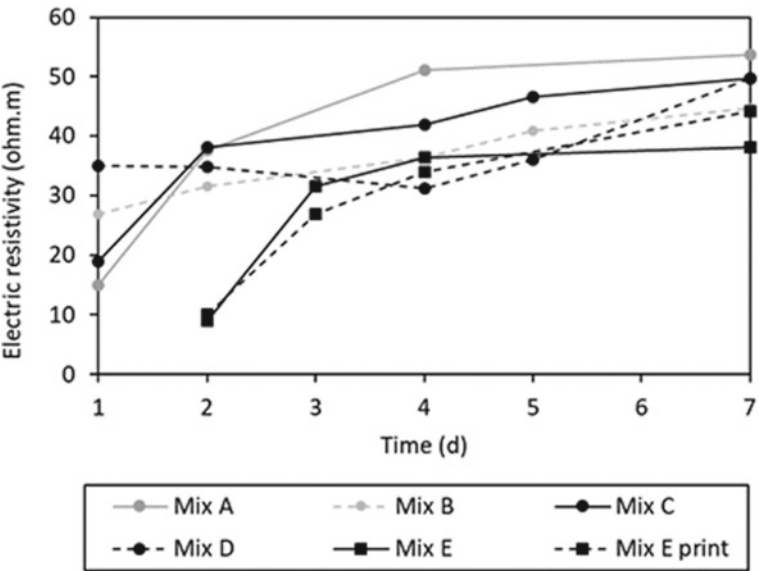


Fig. 12 Electrical resistivity evolution up to 7 days

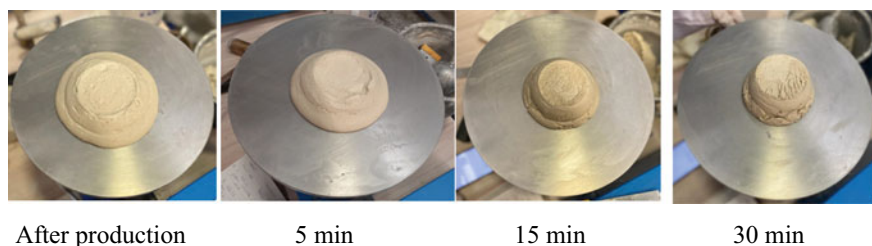


Fig. 13 Slump flow loss for optimal printable mixtures—Mix E

Electrical resistivity was assessed up to 7 days, and results are presented in Fig. 12. As expected the resistivity increases with time, translating the hydrations of cementitious materials, leading to finer pore network with less connectivity [26]. Resistivity results at 7 days ranged from 38 to 53 Ω m, which indicates a very compact matrix. As a reference, after 10 years a dense-aggregate concrete incorporating >5% silica fume, submerged at 20 °C, is expected to exhibit a resistivity from 300 to 1000 Ω m [26]. Mix A showed the highest gain in resistivity, achieving 53 Ω m after 7 days, which is expected since more water was available for the cement hydration process (high w/c). Figure 12 also suggests that the resistivity of all mixtures will continue to increase further beyond the 7 days. Mix E and Mix E print present a similar pattern, with slightly higher electrical resistivity observed for Mix E print.

Analysing integrated fresh and hardened tests, it was decided to proceed with scale-up with Mix E. Before scale-up, a slump loss test was performed (described in Sect. 2.5) to ensure that the mix preserved as far as possible pumpability and extrudability during scale-up printing process. Figure 13 depicts the visual results of slump loss, and Fig. 14 presents the slump values, both after production, 5, 15, and 30 min. As expected in the first minutes, the mixture kept thixotropy behaviour, and after mixing, it kept the slump almost (5 min). At 15 min, a significant slump loss occurred (10%, from 135 to 121 mm), and after 30 min slump was 114 mm (16% loss). As best of the author's knowledge, scale-up processes usually give rise to more fluid mixtures thus Mix E proceeds for 3D printing.

4.2 Full-Scale 3D Printing

The printing process was transversal work among the authors (civil engineering), mechanical engineering and production. Since it is a new subject, some challenges were faced, such as (i) delay time between production and printing effectively starts since several adjustments in CNC machines were needed, (ii) as a consequence, some workability was lost; (iii) before effectively printing the planned objects (presented in Fig. 6) there is a need to perform a trial print to check the pressure, pumping and tubes; (iv) sometimes the nozzle speed was not appropriate since the machine controls it based in the consistency of the fresh composite. Figure 15 shows the printing process

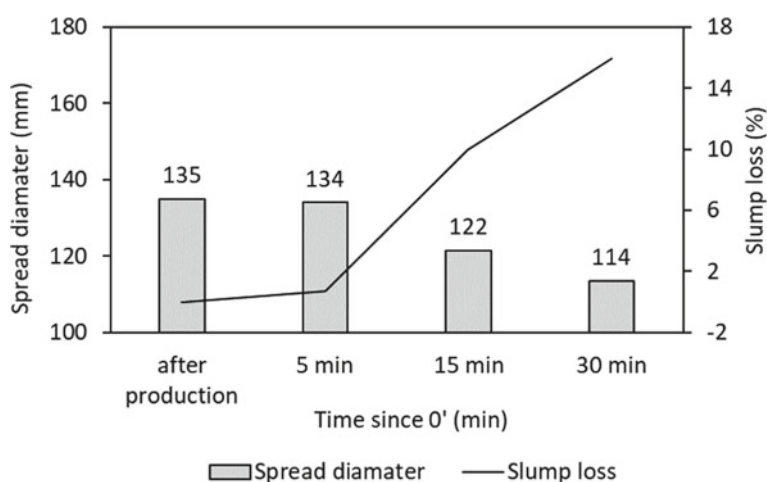


Fig. 14 Slump loss values and percentage of Mixture E

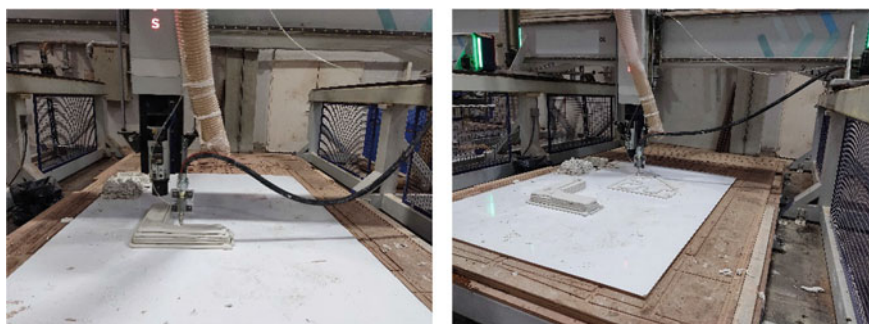


Fig. 15 Printing process

of the objects under study. The first object was a “L” shape constituted by 5 layers of 3DPCC, see Fig. 16, and it presented a very good finish and perfect white colour. The second object, a hexagonal shape with curves inside, is presented in Fig. 17. As can be seen, it also presented a very good finish and colour. Both extrudability and buildability were observed for the printed objects. Those properties and good finish were achieved thanks to the optimised granular packing, in which binder (cement and MTK) involved the aggregate fraction.

After production, the slump flow was 142 mm, and after printing corresponded to 116 mm, representing a slump loss of 21% in a period of 1 h. This corroborates the slump loss test performed previously in small scale batches (1.2 L), described in Sect. 2.5 and discussed in Sect. 4.1, in which a slump loss of 16% occurred after 30 min.



Fig. 16 Printed object “L” shape



Fig. 17 Printed object “hexagonal” shape

Besides, resistivity evolution was similar in Mix E and Mix E print, with a slight increase of full-scale mixture at 7 days. The same trend was observed concerning mechanical strength in which similar results were achieved in Mix E and Mix E print, as can be seen in Fig. 12.

5 Conclusions and Final Remarks

New techniques and methodologies appeared to design, plan, and build in the XXI century. Adopting the paradigm of Industry 4.0 thought 3DP buildings can benefit particularly the construction sector towards faster production, improved competitiveness along the entire value chain, reducing environmental impact and enhanced worksite safety, creation of high-end, technology-based jobs and less risky.

The current work demonstrated that 3DP is a transversal work subject involving several fields, such as materials science, mechanical engineering and production. Even though some difficulties were found in the scale-up process, it was possible to print proposed objects with good finish and colour requirements for architectural applications. In addition, mechanical performance complies with typical values for façade elements. In particular, the current work add insight on the concept of 3D printing for precast industries, and the main conclusions can be summarised as follows:

- 3DPCC can be prepared using locally available raw materials and only superplasticiser without compromising engineering properties, namely at fresh state, such as plastic shrinking and segregation.
- In addition to the slump flow test, which is a simple and common test method to assess the 3DPCC consistency, Casagrande can also provide practical knowledge about the printability of test results.
- The manual printing tests developed using plastic hand extruders can be an easy and economic way to check printability, extrudability and buildability before the scale-up process.
- Although this study did not mainly focus on mechanical strength, the compressive strength of the mixtures were satisfactory based on the 2 and 7-day test results.
- The optimal printable mixture was obtained without HPMC, with $w/b = 0.33$, $SP/p = 1.96\%$ and $\text{cement/sand} = 1.2$
- Slump loss procedure was performed on the optimal mixture, and a decrease of the slump of 16% was obtained after 30 min. It must be emphasised that a set retarder admixture may be needed in larger field productions to avoid consistency loss.
- Printed objects presented a good finish and a perfect white colour that fit architectural requirements.

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3D Print with Salt



Vesna Pungercar , Martino Hutz , and Florian Musso 

Abstract Sustainable materials and additive manufacturing have the potential to increase material efficiency and minimize waste in the building process. One of the most promising materials is salt (sodium chloride). It is highly available as a residue of desalination and potash production processes and attracts attention due to its material properties (storage of humidity and heat). This research presents an investigation and evaluation of using salt as an alternative material in additive manufacturing. Thus, the focus of the study was on small-scale 3D printing with paste extrusion. Experimental studies of different salt mixtures with different binders, printing properties and other parameters were analyzed in three stages. In the first phase (P1) the mixing ratio of salt and potential binders (clay, gypsum, cement and starch) was defined; in the phase two (P2) the most promising mixture was selected, modified by additives and investigated by 3D image scan measurements; and in the last third phase (P3) the potential applications of salt in additive manufacturing were presented. As the research shows, the salt in material extrusion processes can substitute the main material by up to 70%, is successfully manipulated with different additives (to improve the workability of the printing mortar) and is highly dependent on the printer's settings. For future full-scale 3D printing with salt many steps still have to be taken. However, incorporating salt in additive manufacturing showed a potential of saving material resources, addressing environmental issues and initiating new construction processes.

Keywords Salt · Additive manufacturing · Experimental studies · Potentials · Sustainability of materials

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1 Introduction

Building materials are of great importance for our society and are used to protect us from the outdoor weather conditions and to influence our physical/psychological well-being [1–3]. However, meeting world material needs is becoming more difficult each year due to the growth of the world population [4], increasing climatic changes [5] and restricted commercial activities such as the COVID-19 disease [6]. The construction sector is, in Europe, not only responsible for 50% of overall material consumption but also for the generation of one third of the total waste and 5–12% of total European greenhouse emissions [7]. So finding more available, affordable and environment friendly materials and using more efficient technological processes such as 3D printing will help to save material resources and minimize the impact of the whole building process [8–10].

1.1 Salt as a Resource

One of the new promising materials is salt (sodium chloride), which has been a valuable material for many centuries. During the past decades it has attracted wide attention as a residue of desalination and potash production. Due to increasing demand for fresh water and its limited supply, almost 47% of the world population does not have enough fresh water for at least one month each year [11]. In some coastal areas seawater has been used as a resource for producing fresh water. The process of extracting fresh water from seawater and discharging the residue (hypersaline brine) into the sea is called desalination. Around the world, some 15,906 operational desalination plants (see Fig. 1) produce a total of 95 million cubic metres of desalinated water per day and an estimated 142 million cubic metres of hypersaline brine, of which approximately 8.45 million cubic metres of salt per day are disposed into the sea [12]. In terms of its origin, 70.3% of global brine disposal comes from the Middle East and North Africa, 10.5% from East Asia and Pacific, 5.9% from Western Europe, 3.9% from North America, 3.9% from Latin America and Caribbean, 2.6% from Southern Asia, 1.8% from Eastern Europe and Central Asia and 1.0% from Sub-Saharan Africa. The disposal of hypersaline brine into the sea and its negative



Fig. 1 Desalination plant in RAK (Ras Al Khaimah, United Arab Emirates). Licensed under the Creative Commons Attribution 2.0 Generic license. *Source* Wikimedia Commons [17]

environmental consequences have already been acknowledged in scientific research. The observed negative effects include; change of water quality (increase of salinity, temperature), less light passing through the water (due to the growth of algae), and a reduction of biodiversity (fish, corals) [13–15]. At the moment there is a lack of regulation for brine disposal into nature, although measures such as brine discharge system configurations or the reuse of the brine are proposed in different research projects [14, 16].

Another source of salt waste (NaCl) is the potash industry [18]. Due to extensive agriculture, many fertilizers are used to enhance crop growth. One common fertilizer is potash as found in sylvite and carnalite minerals [18]. The remainder of the minerals consists of salt (NaCl) and small amounts of clay, silt, sand, and dolomite [19]. Taking into account that annual global production presents around 68.1 million tons of potash [20], salt waste (83.5 wt% of the mineral) can be calculated at around 335 million tons a year. Salt waste from mining (see Fig. 2) is also disposed into nature as salt tailing on the surface [18], as brine injection/backfilling underground or as direct discharge to rivers and seas [21]. One of the best known salt tailings in Germany is the roughly 250 m high “Monte Kali” composed of 236 million tons of mining salt waste [22]. It has been discovered that the salt contamination to nearby waters are clearly caused by the salt load and prevents “a permanent recolonization by typical sensitive freshwater species” [23]. In Spain and Canada researchers discovered various negative environmental effects caused by potash mining activities: a decrease of water conductivity and the number of living communities in the Llobregat Basin [24] and a devastating impact of high salt concentration in the rivers near Saskatchewan’s potash mines [19]. If the world’s annual salt waste were spread on the surface of the city of Munich (310.43 m²) a 54 m-high layer of salt would be created within 5 years.



Fig. 2 Potash tailings stack Monte Kali, Heringen, Germany. *Photo: Vesna Pungercar, 2020*

1.2 Salt Properties

Sodium chloride or table salt is one of the best-known substances on the Earth. It consists of two different elements: Na (Sodium) and Cl (Chloride), which are linked by an ionic bond [25, 26]. Salt crystals come in different sizes, are white and without smell [27]. Microscopically observed, salt does not have many open spaces in its structure and is known for its low permeability and porosity [28]. Literature records sodium chloride's specific heat as between 0.853 J/(gK) [29] and 0.859 J/(gK) [30, 31]. The thermal conductivity of salt varies from 6 to 6.5 W/mK at room temperature [29, 32–35] and 3.3 W/mK at higher temperatures (approx. 300 °C) [35]. Salt melts at 801 °C [36, 37] and is used for heat storage in solar power plants [37].

In addition to the properties noted above, salt can dissolve in water, methanol or formic acid [29]. At a relative humidity above 75.3% [29] salt crystals start to dissolve and change to brine (salt with water). However, in the drying process the water evaporates and crystals start to grow again. During the past decades, salt rooms have been developed and used for drug free treatment of respiratory illness, skin diseases [38] and lung cancer cells [39]. The treatment consists of sitting in salt rooms, salt caves or at the seaside and breathing air saturated with salt particles (aerosols) [40, 41]. Several studies focus on the positive effect of treatment with a saline environment [39, 41–43], but unfortunately no research has been conducted about how salt as construction material impacts the quantity of aerosols in indoor environments and health.

1.3 Salt Materials in Building Construction

In historic building construction, salt materials were mostly used in dry-hot weather conditions and in locations where conventional resources were not available. In some cases, salt materials were cut from nearby salt seas or mines and used directly as a building block for exterior walls [44–46]. One of these buildings is the hotel “Palacio de Sal” in Salar de Uyuni in Bolivia (Material District 2016), which is built out of about a million salt blocks. Other salt-based construction materials are mixtures of salt and different binders (clay, volcanic ash, cement or starch) [44, 47].

Karshif and Roman maritime materials are among the oldest existing mixed salt materials. Karshif, from the Siwa Oasis in Egypt, is a material for load bearing walls made of small salt rocks (up to 95% of the material) and salt-clay mortar [44]. Due to its hygrothermal and chemical properties, Karshif stone can be formed to “a sort of monolith” [48] under repeated cycles of absorbing humidity from the environment and emitting it again. The Romans mixed volcanic ash, lime and seawater [49] to build highly durable protection walls in the Mediterranean sea. Different studies on the long-term compressive strength of concrete made with seawater discovered that there is almost no difference to that of concrete mixed with freshwater [50–52]. Other mixtures of concrete and salt were developed for the protection of radioactive waste

in abandoned salt caves [53–57], here salt comprised around 50% of the whole mass [53].

Further salt materials may be produced by pressing, melting, additive technology or natural salt crystallization. Salt lick blocks [58] are made of compressed salt as an additive to animal nutrition and dissolve with animal saliva [59–62] if they do not contain special additives [63] or coatings [62]. Salt crystallization processes are used in contemporary art and architectural structures by soaking different materials in very salty water or leaving materials outside to dry. Over time, salt crystals grow and create salt crusts which are also used as artworks or as shading systems [64–67].

New salt mixtures (salt and starch) have gained attention in the last decades as a result of a recent building technology made possible by advances in data processing—additive manufacturing [68–70] (see Fig. 3). The first 3D printing prototypes were developed by a research team at the Solheim Additive Manufacturing Laboratory of the Mechanical Engineering Department of the University of Washington [68, 69] (see Fig. 3). Their 3D printed elements were composed of salt (8 parts by weight), maltodextrin (1 part by weight) and water. The same recipe was later adapted and slightly modified by researchers from Emerging Objects to create a 3D-printed salt pavilion [71] (see Fig. 3) and by TU Delft to examine mechanical properties of the salt-starch mixture [69]. Researchers from Japan mixed salt-starch with wheat flour and dextrin to create 3D moulds [72].



Fig. 3 Left—additive manufacturing. Right above—the first 3D printing salt prototypes. Right below—the 3D-printed salt part for a 3D-printed salt pavilion. *Source* Left—TUM EBB. Right above—The Solheim Additive Manufacturing Laboratory of the Mechanical Engineering Department of the University of Washington [68, 69]. Right below—Emerging Objects/Ronald Rael and Virginia San Fratello [71]

1.4 3D Printing with Salt

As a porous material salt has a potential in additive manufacturing processes if it can be bound. There are various methods in additive manufacturing such as binder jetting, fused deposition modelling and paste extrusion. However, the most common processes that have been used with salt are binder jetting [68, 69, 71, 72] and paste extrusion. Binder jetting was invented almost 30 years ago at the Massachusetts Institute of Technology [69] and generally includes spreading a thin layer of powder, depositing a binder on the powder, repeating the first two steps multiple times and if needed applying a heat treatment [73]. Paste extrusion includes mixing solids with a liquid binder, pushing the paste through a nozzle, thus creating an object layer by layer from the bottom up [74] (Fig. 4).

Dr. Mark Ganter and his team from University of Washington [69] were the first to use binder jetting for salt and succeeded in creating the first, very small 3D printed objects (up to 5.2 cm). Only some years later a research team from “Emerging Objects” used the same 3D printing process and powder mixtures (salt and maltodextrin) but a different binder (rice wine). They developed 3D printed salt elements which were light, translucent and waterproof due to a coating with wax. 330 salt printed elements were connected to create a salt pavilion called Saltygloo [71]. This recipe was also used by a student from UC Berkeley to print his 3D master-thesis model [75].

Paste extrusion processes with salt were examined by the researcher and designer Karlijn Sibbel who managed to print small 3D printed salt objects with a low height (less than 10 cm) and a low quality [76]. Unfortunately, we were unable to find any scientifically relevant information about the mixtures and the process. Japanese [72] and Swiss researchers [77] have been investigating the creation of salt scaffolds by paste extrusion which can later be removed by soaking the object in water (salt leaching).

Most previous research in this area has focused on salt materials’ properties themselves rather than whether the salt materials are appropriate for 3D printing and which additive manufacturing process is the most appropriate for salt. As a consequence



Fig. 4 Left and right—a 3D-printed salt pavilion. *Source* Emerging Objects/Ronald Rael and Virginia San Fratello [71]

of the increase of building with 3D printing devices on construction sites, a better understanding of the interaction between 3D printing materials and additive manufacturing is growing. Nevertheless, the challenge of using more resource efficient materials in 3D printing persists. In this paper, we address these research gaps by using salt waste as a means to improve the resource efficiency of printing materials and to evaluate advantages and disadvantages of using it in paste extrusion processes.

2 Experimental Studies

The main objective of our three experimental studies is to create and evaluate salt mixtures in small-scale material extrusion processes and collect information for future research with large-scale 3D printing. All 3D printing experiments were conducted with a clay printer called “Potter Bot Micro 10” at the “Low-Cost-Lab” of the Chair for Design, Construction and Materials (EBB) at the architectural faculty of the Technical University of Munich.

The goal of our study was to evaluate all parameters that influence the quality of printed objects. These parameters are: printer properties (printing speed, extrusion flow rate, nozzle size), material properties (mixing ratio, water content, type of binder, other components) and other modelling or thermodynamic processes (heating the mortar, drying 3D printed objects in the oven).

The literature reveals various methods for evaluating the quality of printed objects [78–80]. We analysed the printed salt objects in three stages using different methods. In the first phase (P1) the mixing ratio of salt and potential binders (clay, gypsum, cement and starch) was defined by continuously improving the quality of the printed objects [81] and evaluating it with printability criteria found in literature [82]. In phase two (P2) the most promising mixture was selected and further modified by using different additives. Then the mixtures were analysed by 3D scan and image measurement methods [79]. In the third phase (P3) potential applications of salt mixtures in 3D extrusion processes were analysed and printed at small-scale. The materials used in these studies were salt, clay, Portland cement, silica sand, starch (maltodextrin), water and gypsum, their properties are listed in Table 1.

2.1 *Experimental Study 1: Salt/Binder*

2.1.1 Material

In this experimental study, the advantages and disadvantages of salt materials in paste extrusion processes were analysed. After identifying potential binders in literature, we investigated the mixing ratio of salt and binder. Again, the materials used are listed in Table 1.

Table 1 Materials used in the all phases

Material	Producer	Product properties
Salt (NaCl)	Diacleanshop	White colour, pharma quality, Eur. Ph. USP, MG 58.44 g/mol, grain: 1 mm
Clay	Sibelco	WM2505, white colour, Firing temperature: 1000–1300 °C Firing color: light cream–light grey, grain: 25% with 0–0.2 mm grain size
Portland cement	Solnhofen Portland Zementwerk GmbH	Normal cement CEM I 42.5 N, normal early strength, normal post-hardening, normal hydration heat development
Silica sand	Sika	Grain: 0.063–0.3 mm
Natural gypsum	Diacleanshop	Calcium sulfate dehydrate, powder
Starch (Maltodextrin)	Myprotein	100% maltodextrin carbs, powder
Alcohol (Isopropyl)	spinnrad	2-Prapanol, 99.5%

Four typical salt mixtures were named according to the composition of salt and binder: SS (salt and starch), SC (salt and clay), CS (salt and concrete) and SG (salt and gypsum) [81]. The SS mixture is the most frequently used salt mixture in binder jetting process [68, 69, 71, 81]. The SC mixture is still unknown in 3D printing. However, it has existed as a traditional material for 2600 years in the Siwa Oasis, Egypt [44]. CS is based on a mixture common in concrete construction (Portland cement, silica sand and water) without any additives (bentonite or superplasticizer). The SG mixture consists of gypsum, salt and water and its main challenge was expected to be the speed of the drying process.

2.1.2 Methodology

The mixing ratio of salt and binders was defined by experiments in which the salt mixtures were continuously improved [81] and at the same time evaluated with visual printability criteria such as pumpability, printed shape consistency, proper binding time, acceptance for building up another layer and smoothness of the surface [82]. The first prototypes were mixed in a pot (A) and experimentally printed by hand injection onto a transparent Plexiglas plate (B) in a circular form of up to three layers, hardened at indoor room temperature and evaluated after one to three days (C) (Fig. 5).

Table 2 shows the four salt groups (SS, SC, CS, SG) with 6 mixes each (recipes from A to F), exploring the application in additive manufacturing. The initial mix of each group is always Recipe A. The following mixes (B–F) were continuously modified following the investigation and evaluation of the previous mix. For example,

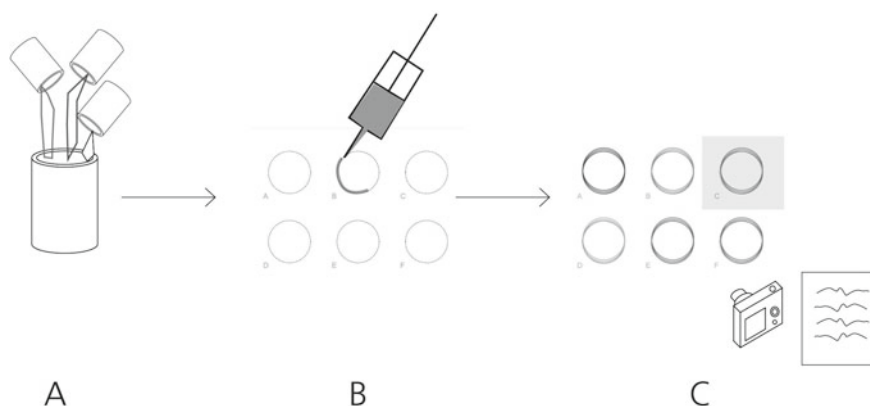


Fig. 5 Method for the experimental study. A—mixing materials, B—experimental printing with hand injection, C—hardening at indoor room temperature and evaluating after one to three days. Image: Vesna Pungercar [81]

if the printing mortar in recipe A was too liquid or too dry, the amount of water was decreased or increased in recipe B. In the event that the mortar in recipe B had appropriate printability, in recipe C the amount of salt was increased to gain higher resource efficiency. The resource efficiency increased with a higher amount of salt in the mixture.

2.1.3 Results

All salt mixtures were evaluated on a basic scale of 1 to 3 according to their poor, median or good printing qualities. 1 represents a maximum score (good performance), 2 a middle score (average performance) and 3 a minimum score (bad performance) (Table 2). The mortar with the highest number of scale 1 grades was considered to be the best mortar and was further examined with our 3D printer (bold in Table 3).

We observed that the conventional and traditional materials (concrete, clay, gypsum, starch) always failed to contribute to an adequate printing mortar when used together with salt in the initial mix. Thus further adjustments depending on the binder were made so that the printing mortar could pass through the nozzle of the hand injection device and stay stable in the 3D object (cylinder).

The SS (salt and starch) mixture had white colour and no odour or salty taste. As described in literature the starch was mixed in warm water to create a substance similar to gelatine and was subsequently mixed with salt. However, the resulting mortar was impossible to print. At the beginning, the mixture was too hard and after decreasing the amount of salt, too fluid. We noticed that the starch increased the viscosity of the mortar so much that at the end all printed layers connected to a circular form of up to three layers and did not stay stable. After drying, the printed object had a translucent, shining and hard surface.

Table 2 The recipes of salt mixtures, *Source* Authors [81]

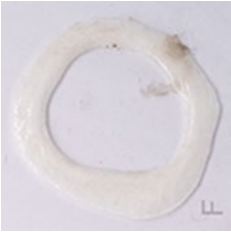
Group	Recipe	Ratio salt: binder	Salt (g)	Clay (g)	Fresh water (g)	Sand (g)	Cement (g)	Gypsum (g)	Starch (g)
SS	A	88:12	352	–	10	–	–	–	48
	B	50:50	200	–	100	–	–	–	200
	C	61.5:38.5	200	–	40	–	–	–	125
	D	21:79	80	–	40	–	–	–	300
	E	46:54	90	–	40	–	–	–	105
	F	30:70	45	–	40	–	–	–	105
SC	A	70:30	280	120	100	–	–	–	–
	B	70:30	280	120	60	–	–	–	–
	C	80:20	320	80	60	–	–	–	–
	D	60:40	240	160	60	–	–	–	–
	E	65:35	260	140	40	–	–	–	–
	F	65:35	260	140	60	–	–	–	–
CS	A	50:50	600	–	210	480	120	–	–
	B	60:40	480	–	190	576	144	–	–
	C	60:40	480	–	190	576	144	–	–
	D	60:40	320	–	104	384	96	–	–
	E	70:30	240	–	104	448	112	–	–
	F	80:20	160	–	104	512	128	–	–
SG	A	50:50	50	–	20	–	–	50	–
	B	60:40	60	–	15	–	–	40	–
	C	60:40	60	–	18	–	–	40	–

(continued)

Table 2 (continued)

Group	Recipe	Ratio salt: binder	Salt (g)	Clay (g)	Fresh water (g)	Sand (g)	Cement (g)	Gypsum (g)	Starch (g)
	D	50:50	50	–	18	–	–	50	–
	E	70:30	70	–	16	–	–	30	–
	F	40:60	40	–	19	–	–	60	–

Table 3 Printability evaluation for salt mixtures. Photos: Martino Hutz [81]

Name	Recipe	Pumpability	Printed shape maintenance	Proper binding time	Possibility to build another layer	Surfaces	Photo of the best mix
SS	A	3	3	3	3	1	
	B	3	3	3	3	1	
	C	3	3	3	3	1	
	D	2	3	3	3	1	
	E	2	2	3	3	1	
	F	2	2	2	3	1	
SC	A	2	3	2	3	2	
	B	1	2	1	1	1	
	C	2	1	1	1	2	
	D	1	1	1	1	1	
	E	3	3	1	3	3	
	F	1	2	1	2	2	

(continued)

Table 3 (continued)

Name	Recipe	Pumpability	Printed shape maintenance	Proper binding time	Possibility to build another layer	Surfaces	Photo of the best mix
CS	A	1	2	3	3	2	
	B	2	3	3	3	3	
	C	2	3	3	3	2	
	D	2	2	3	3	2	
	E	1	2	2	3	2	
	F	1	2	2	2	1	
SG	A	3	3	3	3	3	
	B	3	3	2	3	3	
	C	2	3	3	3	3	
	D	3	3	3	3	3	
	E	3	3	3	3	3	
	F	1	2	3	2	2	

The SC (salt and clay) mixture: had brown colour, a light odour and a taste of soil. Clay, salt and cold water were mixed in a pot. The initial mixture was too fluid, so the amounts of water and salt in the further recipes (B–D) were decreased. Although recipe D had the best printability and workability, the amount of salt was experimentally decreased in the next steps. More salt increased the porosity of the material and influenced the application of the printing mortar negatively. Therefore, recipe D was chosen as the best printing mortar of all clay-salt studies. Its advantages were easy pumpability, keeping the shape and a short binding time (Fig. 6).

The CS (salt and concrete) mixture: had a dark grey colour, a strong odour and a taste of cement. The CS mixture contained at first a mix of cement, sand and salt. Afterwards cold water was added. None of the six of recipes were useable. To push the material through the nozzle the mixture had to be fluid, otherwise it was impossible to print. We suspect that the aggregate content (sand, salt) was too high and congested the injection nozzle. After hand-printing it remained unstable, was not plastic enough and took too long to dry.

The SG (salt and gypsum) mixture had a light brown-grey colour, a faint odour and a taste of gypsum. Gypsum, salt and cold water were mixed in a pot. The initial mixture could be pushed through the nozzle although the stability of the printed object was not perfect. In the recipes from B to E an attempt was made to decrease the water and gypsum content. However, either the mix would not pass through the hand injection device or it was too fluid. At the end the amount of salt was decreased



Fig. 6 (clockwise from top left) Material mixtures, Salt and Starch, Salt and Clay, Salt and Gypsum, Salt and Concrete. Photos Martino Hutz

and the mortar became useable for printing (recipe F). Although the modified mixture performed more favourably than the others, its binding and hardening times were too short.

The best mixture of all salt mortars was salt and clay (SC, recipe D) and was thus further analysed in phase two.

2.2 Experimental Study Two: Salt Cylinder

2.2.1 Material

The most promising salt-clay mixtures from experimental study one (P1) were further analysed and refined in this second study (P2). The goal was to investigate the influence of salt and additives on the printing quality of 3D printed cylinders. Different additives were used to improve the surface quality and change the viscosity (starch) as well as structural stability (straw) for potential applications. As the salt-starch-mixtures from the experimental study one did not show positive printing properties, the objective was to further investigate starch-salt-clay mixtures. To influence viscosity and gain control over the efflorescence, starch with alcohol (Table 1) was added to the salt-clay mixtures: Alcohol lowers the solubility of starch by attracting water and prevents the formulation of non-Newtonian fluids (only starch and water). To improve the overall stability in the salt-mixtures a natural reinforcement material was tested. Since the 3D printing process and traditional steel reinforcement are not very compatible, fine fibres were added to the material mixture similar to GFRC (fibre reinforced concrete). Straw was selected for its widespread availability and positive thermal potential.

Cylinders of four different materials were 3D printed for comparison: C (clay), CS (salt-clay), CSS (salt-clay-straw) and SSC (salt-starch-clay) (see Fig. 7).

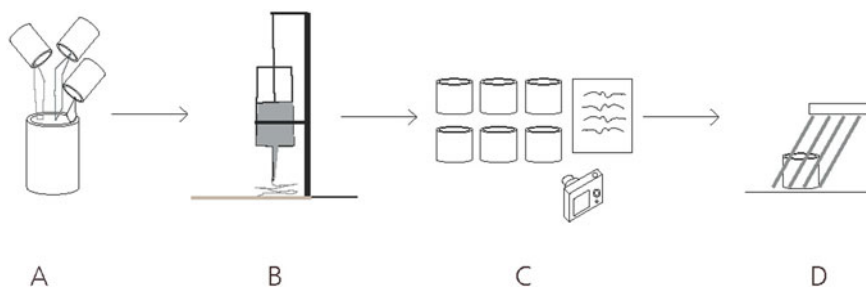


Fig. 7 Method for the experimental study two. A—mixing materials, B—3D printing, C—hardening at indoor room temperature and visual evaluation D—3D scanning and evaluating the cylinder.
Image Vesna Pungercar

2.2.2 Methodology

The quality of four different cylinders was assessed using visual evaluation and optical 3D scanning methods in four steps (A–D). Step A consisted of mixing materials, step B of 3D printing 19 cylinders, step C of hardening them at indoor room temperature. Step D consisted of optical 3D scanning measurements and evaluating the cylinders (see Fig. 7).

Step A: Mixing Materials

Salt and binders were mixed for a minimum of 10 min to ensure a homogeneous consistency. A “KitchenAid Classic 5K45SSEWH” with a capacity of 4.8 L and a tilt-head flat beater proved to have sufficient capacity and strength for the material mixtures (A).

Table 4 shows the following material mixtures CS: Clay, Salt, CSS: Clay, Salt, Straw and SSC: Clay, Salt, Starch with 6 consecutive mixtures (recipes from A–F). Each group starting with recipe A offering the best results from phase one (P1) or being the best mixture from previous tests.

Step B: 3D Printing

All test cylinders printed were $10 \times 10 \times 10$ cm. Each cylinder was created from 66 printed layers, each one 1.5 mm high. The circular nozzle had a diameter of 6 mm and the printing speed was set at 40 mm/s. The reference cylinder, purely out of clay, was printed in approximately 8 min, however, the time was raised up to 20 min depending on the material mixture. The printing speed and the extrusion factor were individually controlled and adjusted according to the behaviour of the material. The amount of material usage was estimated at approximately 190 g on average. The base cylinder was prepared and sliced in layers with the software Ultimaker Cura, version 4.9.1 and exported as a G-Code file to the printer. One outskirt ring was set and later removed to ensure a continuous extrusion once the main cylinder started 3D printing (Fig. 8, left image, bottom layer offset from the Test-Cylinder).

Step C: Hardening at Indoor Room Temperature and Visual Evaluation

All 19 test cylinders were printed with the same settings for better comparison. However, due to the variation in material mixtures and recipes the overall shape, surface and printability showed significant differences. To further understand the properties of the salt-mixtures, the best printing results were further analysed. One cylinder was taken from each material group (CS, CCS, SSC) and compared. A test cylinder, printed with the same settings and consisting just of clay was added (C) as a reference. Visual evaluation criteria were applied to the material mixtures: pumpability, printed shape maintenance, proper binding time, possibility to build up another layer and surface smoothness.

Step D: 3D Scanning and Evaluating the Cylinder

The successfully printed cylinders were stored to dry at room temperature and were scanned with the optical 3D-coordinate measuring device Keyence, VL. Using this

Table 4 Material mixtures CS: Clay, Salt, CSS: Clay, Salt, Straw and SSC: Clay, Salt, Starch with 6 consecutive mixtures (recipes A–F)

Group	Recipe	Ratio salt: binder	Salt (g)	Clay (g)	Fresh water (g)	Alcohol (g)	Straw (g)	Starch (g)
CS	A	60:40 (1500 g)	900	600	140	–	–	–
	B	60:40 (1500 g)	900	600	190	–	–	–
	C	60:40 (1500 g)	900	600	190	–	–	–
	D	70:30 (1500 g)	1050	450	200	–	–	–
	E	80:20 (1500 g)	1200	300	250	–	–	–
	F	80:20 (1500 g)	1200	300	210	–	–	–
CSS	A	60:40	720	480	180	–	–	–
	B	60:40	720	480	180	–	30	–
	C	64:36	840	480	180	–	10	–
	D	70:30	840	360	180	–	10	–
	E	70:30	840	360	162	–	10	–
	F	70:30	840	360	160	–	10	–
SSC	A	60:40 (1500 g)	720	480	150	15	–	180
	B	70:30 (800 g)	560	240	80	8	–	100
	C	80:20 (1000 g)	800	200	100	10	–	125
	D	78:22 (1150 g)	900	225	140	10	–	140
	E	75:25 (1000 g)	750	250	100	10	–	125
	F	80:20 (1000 g)	800	200	100	10	–	150

Source Authors

equipment it was possible to 3D scan and compare the best prints. The optical 3D coordinate-measuring device allowed us to compare the different cylinders with a precision of 2 μm . The 3D scanning method compares the cylinders digitally, which helps to understand small deflections, inaccuracies or discrepancies at a micro scale.

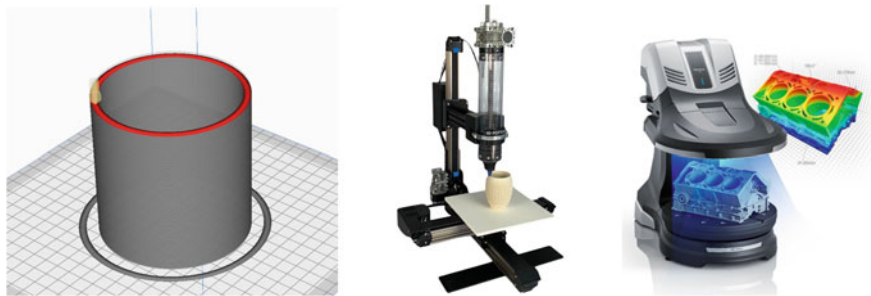


Fig. 8 Cura-test-cylinder (step B). *Photo* Martino Hutz, Potterbot Micro 10 (step B). *Photo* Potterbot, 3D scanner Keyence VL (step D). *Photo* Keyence

2.2.3 Results

Step A–C: Preparation and Selection of the Material

All salt mixtures were evaluated in three categories from poor, median to good printing behaviour. Scale 1 represents good printing behaviour, 2 an average performance and 3 a minimum score with bad printing quality. All recipes were first tested with hand injection to understand the 3D printing potential and to save time in the printer set-up. However we observed a significant discrepancy with multiple recipes between the results of the hand injection and the 3D prints. In many cases the hand injection showed good results but could not be printed with the 3D printer. All printed cylinders, even successful prints, showed discrepancies to the original 3D file. All printed cylinders were slightly smaller than the virtual design. During drying, the cylinder dimensions decreased due to humidity loss. The drying time and level of shrinking varied between the mixtures (see Table 5).

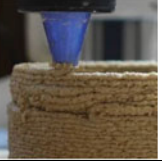
CS-Group: The CS-Group recipes showed different results after being 3D printed. While recipes A–C did not contain enough humidity and clogged in the printing process, recipes E–F showed increasing printing issues with greater water content. Recipe D, being the most successful mixture, was easy to pump by hand injection and had a homogeneous, even surface with a slightly watery consistence. The 3D printed shape was even and air inclusions were covered due to the material consistency. Layers could be built up evenly and the overall surface was homogeneous in all stages. After drying, salt efflorescence occurred evenly on the cylinder (see Table 6).

CSS-Group: Recipes A and B could be printed partially and showed significant problems in stability. Mixtures D–F were increasingly liquid and failed to print full-sized test-cylinders. The best results were achieved with recipe C and a 64:36 ratio. The material mixture printed even layers and was stable. Mixture C showed good results in printing by hand injection as well as with the 3D printer. The overall shape looked good and the full test cylinder could be printed. The layers connected despite the overall rough and porous surface. Due to the added straw, the binding time was significantly longer in comparison to the other mixtures (see Table 6).

Table 5 Evaluation of the 3D prints and material mixtures

Name	Recipe	Pumpability	Printed shape maintenance	Proper binding time	Possibility to build another layer	Surfaces	Photo of the best mix
CS	A	3	–	–	–	3	
	B	2	2	–	–	–	
	C	1	1	–	1	1	
	D	1	1	–	1	1	
	E	3	–	–	–	–	
	F	3	–	–	–	–	
CSS	A	2	2	3	3	1	
	B	2	2	3	3	3	
	C	1	1	3	1	2	
	D	2	2	3	3	3	
	E	3	3	3	3	3	
	F	3	3	3	3	3	
SSC	A	1	1	1	1	1	
	B	1	1	1	1	1	
	C	–	–	–	–	–	
	D	3	2	3	3	1	
	E	1	2	2	1	1	
	F	1	3	2	2	1	

Table 6 Process material mixture-preparation, Photos: TUM students

Name	Mixing materials	3D printing process	3D printed cylinder	Surface
CS				
CSS				
SSC				

SSC-Group: Recipe A showed positive print results and was easy to pump both by hand injection and 3D printer. The reference shape could be printed without shifting or distortions. The layers connected easily and therefore created a homogeneous and even surface on the cylinder. Recipes B–F became increasingly weaker. Recipe A produced the best results and was therefore used for future prints within the SSC-Group (see Table 6).

Step D: Optical 3D Scanning

The overall scan illustrates the discrepancies with colour coding as well highlights the biggest differences between the four cylinders (C, CS, CSS, SSC) compared to the intended geometry (3D model) (see Table 7). The colour code represents a deformation scale. Dark blue represents a negative offset of -10 mm whereby red indicates the maximum extension of 10 mm. The smallest offset (± 0) is represented in light green. Neutral colour indicates that the discrepancy to the base geometry exceeded the 10 mm offset. After optical 3D scanning the images of cylinders, horizontal and vertical cross-section plots (positions 1–4 in Tables 5 and 6), also called surface profiles, were created to quantify the discrepancies. The horizontal section allowed the comparison of the layers width at a given height (50% print) for all prints and visualizes the discrepancy to the outer surface (in yellow) as the reference. The vertical section illustrates the material behaviour and deformation in height. The digital base geometry for comparison was a single surface with the dimensions 10×10 cm.

Table 7: Overall scan illustrates the discrepancies to the original geometry (dark blue = negative offset of -10 mm, red = the maximum extension of 10 mm, light green = the smallest offset (± 0), neutral colour = the base geometry exceeds the 10 mm offset).

C Mixture: As intended for better comparison the model only showed small deviations. The commercial clay had homogeneous and fine-grained material properties and thus this mixture showed the best results. The scan of the clay-cylinder showed overall small deviation from the base model. Local deflections are due to mechanical inaccuracies or air inclusions within the material. It can be observed that the lower layers extend unevenly due to the material weight. Slight discrepancies are also visible in the horizontal section in comparison to the original base model, with the highest values of 1.458 mm to the cylinder outer surface. The vertical section confirms the slight extension at the base layers, however, stays at a 1 – 4 mm difference from lower to higher measuring point.

CSS Mixture: The best results of the clay-salt-straw mixtures showed, in the overall evaluation, a straight wall built up and acceptable deformations (see Tables 7, 8). However, the horizontal section shows significant deviations from the original shape. Shifts in a range between 3.121 and 3.751 mm confirm the already visible material roughness. We observed that due to the straw, the material mixture dried and shrank differently than the other test-cylinders. The 3D scan shows interruptions due to the surface roughness as well. The vertical section confirms the uneven surface with significant variations.

Table 7 Overall scan illustrates the discrepancies to the original geometry (dark blue = negative offset of -10 mm, red = the maximum extension of 10 mm, light green = the smallest offset (± 0), neutral colour = the base geometry exceeds the 10 mm offset)

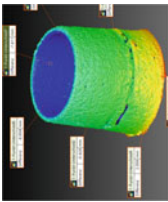
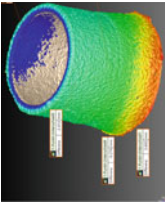
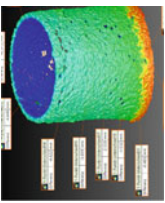
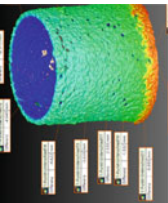
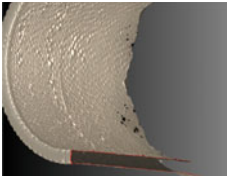
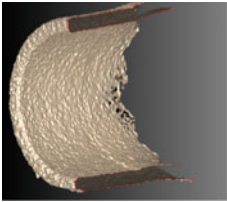
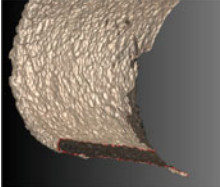
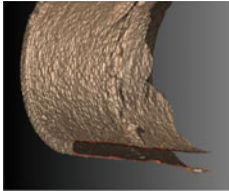
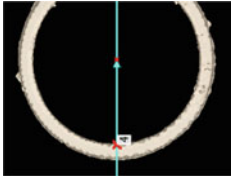
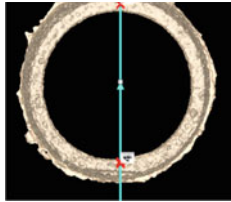
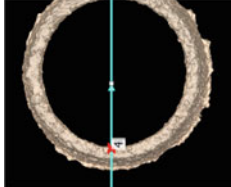
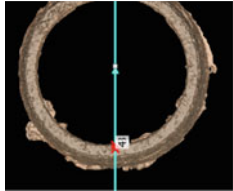
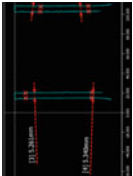
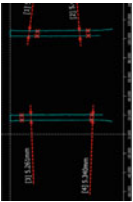
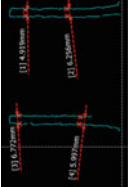
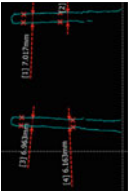
	C	CS	CSS	SSC
Recipe	Clay	Clay, salt	Clay, salt, straw	Clay, salt, starch
Discrepancy to the outer surface				

Table 8 Vertical sections illustrate discrepancies to the original geometry

	C	CS	CSS	SSC
Recipe	Clay	Clay, salt	Clay, salt, straw	Clay, salt, starch
Bottom left width (mm)	5.340	7.103	5.997	6.163
Bottom right width (mm)	5.436	6.848	6.256	7.865
Upper left width (mm)	5.261	6.684	6.772	6.963
Upper right width (mm)	5.021	6.703	4.919	7.017
3D scan section				
3D scan section-line				
3D section width (mm)				

SSC Mixture: The test cylinder of the clay-salt-starch mixture showed only small differences to the original shape (see Tables 7, 8). Besides mechanical inaccuracies at the lower third, the overall print showed no significant deviations. The horizontal section confirms the overall appearance and captures deviations of only 1.3 mm. The vertical section, due to the starch additive, further proves the good characteristics of the overall surface.

All measurements were compared with the modelled 3D surface (see Tables 7, 8). None of the prints matched the assigned dimensions. This illustrates that during the printing process deflections and distortion occur even without visible damages. With higher heterogeneity and lower humidity the printed quality declines. Larger grains or additives also cause an increase of the deviations. Further, while increasing the humidity improved the printability, it also weakened the substance and thus caused more substantial deviations during the drying process. We noted that all scanned cylinders show an uneven distribution of the material at the base. Our assumption is that this effect, not noticeable to the human eye, was caused by a small inclination of the baseplate. In future research the material properties and behaviour for the 3D printed objects have to be evaluated at a 1:1 scale model and with a bigger sized printer to further develop the mixtures.

2.3 Experimental Study 3: Potential Application

To accompany this research, our chair (EBB) also organized two elective master courses in winter semester 2020 and summer semester 2021, whose focus was to extend the knowledge of salt-mixtures, the historical significance of salt as well as potential applications of the 3D printed salt-mixtures. Research of already established applications of salt in everyday life was categorized to understand future fields of application for 3D printing with salt (see Fig. 9).

Using salt as a local and environmentally friendly resource (geographical usage): This approach is based on the concept of building with local materials in dry and hot areas where little rain falls and salt waste is available from desalination plants or potash mining. Materials found on site can be 3D printed and used for buildings. To find suitable locations for this approach, weather data need to be overlaid onto maps showing areas with salt waste. Once defined the use of salt as a building material can be trialled in the identified regions (see Fig. 9, Left above).

Modular prefabricated elements: 3D printed building-elements fabricated off site from salt-mixtures are installed on sites with the right weather conditions. If the humidity is below 75% but high enough to fuse the salt-crystals without dissolving, the separate building elements will join and work as a unified element (see Fig. 9, Middle below)

Health/respiratory applications: This approach focuses on maximizing salt-rich surface area assuming these particles are released over time due to air circulation in indoor spaces. This concept focuses on the medical application of salt for respiratory ailments (see Fig. 9, Right above).



Fig. 9 Student work: Shiyu Chen, Kai Lin, Simone Gabbana, Mehmet Yolcu, Katharina Broghammer, Philipp Neumann, Gabriele Mikalauskaite, Pinar Sel, Malaz Attar, winter semester 2020

Salt as air filter: Salt particles in the air are renowned for clearing the lungs and helping asthmatic patients. This principle was the inspiration for the design of a breathing shelter, where the chimney effect was used to intensify the airflow within the space and to strengthen the therapeutic working (see Fig. 9, Left above).

3D printed salt-mixtures for antiseptic applications: A differentiation of surfaces for interior spaces can be utilized in a more meaningful way: The usage of 3D printed salt-containing surfaces can be used for antiseptic purposes; reducing germs on surfaces but also controlling the growth of specific plants. This project focused on green walls, allowing only salt resistant plants to grow (see Fig. 9, Right below).

3 Discussion

3.1 3D Printer

All experiments were performed with the Potter Bot Micro 10, which is designed for 3D printing with clay, principally used for the printing of ceramics. The ideal material for 3D printing is, by default and as suggested by the manufacturer, a fine grain clay:

“Maccabees cone 5 stoneware” clay or similar is suggested by the company; the printer is not designed to print concrete or other tough materials by default. A block of clay (10 kg) was separated into smaller pieces with a micro fiber towel placed in between to spread the approximately 350 ml of added water equally in the block of clay. The preparation and soaking process took two to three days.

The chair purchased the Potter Bot Micro 10 for the first test series due to its simple technology and construction. The main advantage for the material-tests is the direct extrusion. A threaded rod, controlled by a stepper motor, presses the material directly through a plexiglass cylinder out through the nozzle onto the printing bed: Other printers use compressed air systems with their elements connected with long tubes to process the material, which could cause clogging and corrosion. The maximum material capacity of the printer’s cylinder is 1000 ml and the maximum printing envelope is X-280 mm, Y-265 mm and Z-305 mm. While the cylinder with the material and nozzle only moves vertically, the base/print-bed (266 mm × 266 mm) moves in the X and Y directions to enable full 3D movement. The printer is WIFI controlled with a built-in web interface and can read and print common G-code files. All prints were set up with CURA as slicing software. The speed, Z position and material output can be changed during the print process and adjusted to the material’s behaviour.

The printer properties of the Potter Bot Micro 10 and the material-mixtures are highly dependent on each other. The test results derive from the behaviour and capacities of this printer and are likely to change with bigger and more powerful printers. Since the printer is designed to print clay, our salt mixtures (salt-cement, salt-gypsum etc.) showed less convincing results.

3.1.1 Print Speed

According to the manufacturer, the print speed of the Potter Bot Micro 10 is recommended within a range of 30 mm/s to 60 mm/s, and a maximum of 130 mm/s. The speed is dependent on the material mixture and needs to be adjusted accordingly.

The fastest speed for a defined print result (see 2.2 Experimental study 2: Salt Cylinder) was reached with processed clay. The main factors behind the need to reduce the print speed were dryness and porosity of the material due to lack of water or increased sand/salt ratio. The lower three layers on the printing bed were printed with only 20% of the defined speed in the original CURA file to ensure sufficient contact to the baseplate. Another reason to limit the print speed is the printer construction: If the speed increases, the X–Y controlled base starts shaking and inaccuracies in the print appear; detached and crooked layers that eventually cause the print to collapse. Even though the speed had to be slightly adjusted in each print, a speed of 25–30 mm/s was proven to print the best results with all material mixtures.

3.1.2 Nozzle

The Potter Bot Micro 10 comes with a range of four anodized aluminium nozzles (3, 4, 5, and 6 mm). However, 3D printing with salt mixtures revealed that only the 6 mm nozzle was appropriate as smaller nozzle sizes caused clogging. Due to an increased instability of the clay caused by adding salt (see 2.2 Experimental study 2: Salt Cylinder) narrower layers resulted in shaky and collapsing test cylinders. Material mixtures with sand components (sand grain between 0.1 and 0.4 mm) caused immediate clogging even with the 6 mm nozzle. Sand grains (in combination with clay and salt) interlocked immediately as pressure on the nozzle was increased.

3.1.3 Printed Layer Height

All test cylinders were printed with a layer height of 1.5 mm since thinner layer heights resulted in the overlapping of material. In relation to the print speed and nozzle size the salt-mixtures were too rough to print clean layers and therefore the material was pushed outwards significantly, increasing the layer width as a consequence. Thicker layers resulted in lack of contact between the each other and led to unsatisfactory test prints.

Additionally, we carried out tests printing with “falling infill”. The Z height was moved upwards by about 200 mm in the source code so that the salt-mixture fell into a prepared mould placed on the printing bed. The shape of the mould needed to match the print bed dimensions but could be individually modified in height.

3.1.4 Printing with Inclination

Several tests were made with different material-mixtures. However, the recommended inclination for PLA (Polylactic Acid, most commonly used for small scale 3D printing) of 45° could not be achieved with any of these. When increasing the salt-ratio the mixtures became more and more fragile and therefore the maximum inclination achieved was approximately 20° (depending on the complexity of the shape as well as the water and salt content).

3.1.5 Replacing Printing Material

Changing the printing material requires demounting and replacing the cylinder, including the removal of the top-part (motor with threaded rod and plate for material compression) and bottom-part (component with nozzle) of the cylinder attachments, each connected with eight screws. Since the cylinder material capacity is limited to 1000 ml, larger 3D prints had to be paused while the material was refilled. The cylinder position needed to be marked manually to retrieve the exact Z position of the nozzle and the tracing of the refill had to be done by hand since the main print program

could not be resumed once paused. This caused discontinuity within the shape as well as of the material finish which was taken into consideration for the material thickness and the design. Larger models needed a wall-thickness of a minimum of 25–40 mm to enable the precise continuation of the print with the second refill.

3.1.6 Printing Scale

The maximum printing envelope, described by the manufacturer as X-280 mm, Y-265 mm and Z-305 mm could not be fully utilized in any of the test-prints. Only prints with maximum dimensions of X-250 mm, Y-250 mm and Z-250 mm showed positive results. We observed that large prints approaching the print size limits became inaccurate at the edges. However, in most test-prints it was the material mixtures that limited the overall model dimensions and not the printer. The 3D prints progressively deformed with higher salt ratios in the mixtures and when increasing the overall printing height.

3.1.7 Printing Time

The test cylinders were prepared with height and diameter of 100 mm. The cylinder was printed with a single-layer wall build-up and therefore no infill. In the samples, the layer height was set to 1.5 mm as to allow rougher material-mixtures to be built up in continuous layers. The single layer wall line was set to a width of 6 mm with a 6 mm nozzle. The print speed was set to 30 mm/s, which resulted in an estimated printing time for the full test cylinder of 19 min (see 2.2 Experimental study 2: Salt Cylinder).

3.2 Materials

3.2.1 Salt and Binders

Salt is too porous to be printed alone and requires the utilisation of a binder to hold the salt crystals together in the material extrusion process. Different material tests with our printer showed clay to be the most appropriate binder. Already in the first phase of the experiments, salt-clay (SC) mixtures showed the best printability. However, the SC 3D printed objects (in comparison to the solid clay mixtures) often showed cracks, voids and roughness on the surface as result of a decrease in stiffness. So, in the second phase of the research we experimented with the addition of starch or straw to SC mixtures. While the SC with starch behaved better (stiffness and ductility were improved), SC with straw was in most cases too hard to press through the nozzle of the printer. The straw absorbed water to an unacceptable degree such that the mixture

was no longer printable. Consequently, only very small amounts of straw could be added.

The experimental studies with other binders showed gypsum to have a too short a setting time, concrete to have a too high amount of aggregates and starch to be too fluid. We expect that with adapted additives (super-plastifier, fly ash, short fibres, retarder) or the application of heat, the printability (flow, compressive strength, setting and drying time) could be improved. However, no such studies were carried out.

3.2.2 Amount of Salt in the Printing Mortar

The main goal of the research was to increase the resource efficiency by using the highest possible amount of salt in salt binder mixtures and still obtain the desired printing properties. The highest amount of salt was reached in the salt-clay mixtures with the addition of starch. The optimal mixture consisted of 57% salt, 24% clay, 88% starch, 8% water and 0.8% alcohol. The ratio of salt and binder here was 70:30, all other mixtures had lower salt/binder ratios.

3.2.3 Surface

Salt crystals on the surface of the 3D printed layers not only contribute to an attractive surface, but may also have an effect on health (not yet scientifically investigated) and hygrothermal properties. Higher levels of surface salt crystals could enhance the infiltration of microscopic salt particles into the indoor air with a positive influence on respiratory health. At the same time, the uneven and rough surface will store heat and humidity more rapidly (max 75%) than a smooth one. However, the prevalence of salt crystals on the surface did not only depend on the salt content in the mixture but also on the additives. Although the salt-clay-starch mixtures contained the highest amount of salt, crystallisation was almost undetectable on the surface (due to the starch's properties). In fact, the most visible crystallisation on the surface was observed with the highest water content in salt-clay mixtures without additives.

3.2.4 Water Content

In all our studies, the water content had to be adapted to the salt content as well as the types of additives and binders. The highest water content (with still acceptable printability) was observed in the salt-gypsum (SG) mixtures of the first phase. In salt-clay mixtures in the second phase the amount of water could be raised (up to 13% mass content) by adding straw and was lowest (8% mass content) when adding starch. Finally, with more salt in the salt mortar the water content could be increased. However controlling the printing mortar properties by addition of salt and water were challenging because the salt/water ratio was never linear.

3.2.5 Reinforcement

Reinforcement (straw) was used in the second phase of the studies to obtain better control of cracks after the drying period. We found that the mortar was only printable with the addition of small amount of straw (up to 0.7% mass content). Already in the mixing phase, the straw reinforcement absorbed a lot of water and during the 3D printing process the mortar often became too dry to print with. The research of a variety of reinforcing fibres and a closer control of their impacts is thus recommended for future studies.

3.2.6 Drying

All 3D printed objects were dried at room temperature or in the oven at 90 °C, and it became apparent that the drying process influenced the shrinkage of the objects: with more cracks appearing with longer drying periods. The shortest drying period was recorded for salt-gypsum mixtures and the longest for salt-clay mixtures with starch. Drying an object in the oven accelerated the vaporization of water and caused more salt efflorescence on the surface.

3.3 *Other Parameters*

3.3.1 Full-Scale Printing with Salt

The experiments explored the use of salt in a small-scale printing process. Further optimization of the salt printing mortar is needed for full-scale printing. Small-scale printing results will probably not be directly applicable to a full-scale print due to a different “relationship” between printer and material. In this study we found that the print mortar had to be adapted to printing properties and to the printer itself. For example a mortar containing too much salt was impossible to push through the printer’s nozzle. Consequently, the amount of salt (maximum aggregate size of the printing mortar) was reduced for better printing results. A similar need for adaptations of the printing mortar in full-scale printing can be expected. The properties of the mortar will have to be controlled by different salt/binder ratios or by the inclusion of additives and adjusting the drying and hardening process (cracks should be minimized and compressive strength for maintaining the intended shape must be ensured).

3.3.2 Influence of Salt on the Compressive Strength

The compressive strength of the 3D printed objects was not specifically investigated in these experiments because the compressive strength of salt-gypsum and

salt-clay mixtures have already been tested in previous studies on salt material properties. Compressive strength tests were performed on cuboids of $40 \times 40 \times 160$ mm following the norm DIN EN 13,454–2. The testing cuboids were placed in a climate room at 60% RH and 21 °C, which negatively influenced the values: All mixtures were extremely porous, almost impossible to test and lost up to 96% of their compressive strength in comparison with the reference (100% gypsum or 100% clay). As a consequence, some salt-clay mixtures were put into the climate chamber again as an experiment for 24 h at 40 °C before testing. The results showed that the strength values of dried salt-clay mixtures (30% salt and 70% clay) increased up to 140% compared with the reference (100% clay). Considering the effects of relative humidity on compressive strength it is thus preferable to use structural salt mixtures in dry and hot climate zone or conditions.

3.3.3 Surface Treatment and Stucco

The process of additive manufacturing produces inherently textured surfaces. The layers, depending on the material, nozzle size and layer height, are staggered horizontally and therefore visible on the outer surface. Adding salt to other materials triggered an increase of porosity and surface roughness, which will have a major influence on the design of potential full size building elements. Depending on the application, the surface would need to be protected from potential damage like humidity, rain or manual impact. The type of protection will need to be analysed in a separate study.

3.3.4 Prefabrication, Field Factories and On-Site Printing

Different construction methods for 3D printing with salt can be considered and will need to be studied. The printing method will depend on the field of application and will have to comply with the constraints of the 1:1 scale printer. Prefabricating 3D printed building parts will have the advantage of a controlled production environment which allows for more complexity and precision of the printed geometry (see Fig. 10). As recently applied in the 3D printing industry for buildings, the printer could alternatively be mounted to print on site. This would especially be attractive for remote areas with high salt resources.

4 Conclusion

In this research three consecutive studies were undertaken to analyse salt mixtures for additive manufacturing in paste extrusion. The intent of this research was to find potential for the use of more salt in the building process. Salt is increasingly becoming an environmental threat as a by-product in desalination plants as well as potash production. However, salt has high potential due of its over-availability and



Fig. 10 Remote 3D printing at Chaka salt lake, master Thesis, Kai Lin, summer semester 2021, TUM

positive properties such as storage of humidity and heat as well as potential positive impact on respiratory health.

The analysed mixtures were made with a small but significant fraction of potential additives, this can be extended with cement, resins or other materials. The research showed promising results and succeeded in integrating up to 70% of salt in the 3D printed material mixtures. However, the tests were limited due to parameters as lab-space, the available 3D printer and the testing facilities. Most of the printed mixtures were less stable with increased salt content, although some results (see Sect. 3.3.2) had an even higher compressive strength, so the need for additives has to be clarified. Straw, as hydrophilic additive, caused increasing surface roughness and segmented layers. The question of the dissolution of salt at above 75% humidity remains to resolve; this can be improved with surface treatments and sealants. It can be seen that by working with 3D printing as new construction method new approaches have to be considered for the salt-mixtures. Prefabrication of “smarter” surfaces or systems for on-site construction is likely to become a relevant field of application. The absence of steel reinforcements in the 3D printing process allows salt to reveal its positive properties instead of causing unwanted corrosion. Finally, 1:1 scale samples need to be printed to fully understand the potential of 3D printing with salt.

Declaration of conflicts No conflicts.

Authorship Contributions Vesna Pungercar: Conceptualization, Methodology, Formal analysis, Investigation, Paper Layout, Resources, Writing - Original Draft (Abstract, 1. Introduction, 2 Experimental studies, 2.1 Experimental study 1: Salt/Binder, 2.2 Experimental study 2: Salt Cylinder, 3.2 Materials, 3.3.1 Full-scale printing with salt, 3.3.2 Influence of salt on the compressive strength, 6 Publication).

Martino Hutz: 3D print strategy, Visualization, Formal analysis, Investigation, Resources, Writing - Original Draft (2.2 Experimental study 2: Salt Cylinder, 2.3 Experimental study 3: Potential Application, 3.1 3D printer, 3.3.3 Surface treatment and stucco, 3.3.4 Prefabrication, field factories and on-site printing, 4. Conclusion).

Florian Musso: Conceptualization, Writing: Review and Editing (All chapters).

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Use of Waste Materials to Reduce Cement and Natural Aggregates in 3D Printing Mortars



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Abstract 3D printing (3DP) is an example of a sustainable technology capable of replacing traditional manufacturing processes. One of its advantages is the use of optimized production processes, even for customized products, as well as the almost non-existence of waste. 3DP mortars (3DPM), therefore, rely heavily on Portland cement (PC), a material with high carbon emissions and energy consumption related to its manufacture. In order to comply with the growing environmental regulations and concerns, it is imperative that its use becomes more moderate and, as such, alternatives to PC or additives to reduce its percentage are being sought. At the Faculty of Engineering of University of Porto, research has been conducted to produce 3DPM with different waste materials. This study has the following objectives: (i) reduce PC by adding sugarcane bagasse ash (SCBA), with a strong emphasis on performance; (ii) substitute natural sand with recycled brick sand (RBS), aiming at replacing a natural aggregate while exploring new aesthetic possibilities. As to assess their viability as 3DPM, several mortars with different amounts of SCBA and RBS were formulated, taking into account some of its fresh and hardened properties as well as exploring different colours and textures. In the end, the best compositions were printed using material extrusion equipment.

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1 Introduction

The Building and Construction sector is known for its outdated methods that lead to not only consuming large quantities of resources and generating significant amounts of waste, but also bringing considerable risks to the workforce. Low productivity is a given in this sector due to the rare use of innovative techniques. The current implementation of new technologies in this industry (e.g. Building Information Modelling—BIM—and 3DP) brought production and automation benefits, while it aimed at improving its sustainability, due to: architectural freedom; reduction of material consumption and waste and a reduction of CO₂ emissions; the equipment's capacity to operate uninterruptedly; reduction of normal constraints during construction (smoke, dust and excessive noise); and capacity of constructing in harsh environments, where the use of manpower is unsuitable [1–3].

According to Deloitte [4], the 3DP technology has been applied in the most diverse areas for the past 40 years, such as arts, medicine, the culinary, automotive, aerospace or toys industries. At first, it was essentially based on the production of low volumes and small part sizes with complex designs; however, technological innovation has allowed a reduction in costs, higher mobility, and a better quality of the equipment, encouraging the implementation of 3DP in a wider range of areas. Thus, larger printed volumes employing a wide variety of materials, which enabled its implementation in the Architecture, Engineering and Construction industries [5], emerged.

There are different 3DP techniques, but the main ones are the Binder Jetting and Material Extrusion technologies. The first one uses a fine grain size material in layers that is held together by a pulverized binder. The presence of layers as support material allows the materialization of more complex geometries. Examples of this creative freedom are the sculptural forms which have already been printed by this technology [6]. The second technique is based on the layered extrusion of deposited materials' filaments. Since there is no support material, the geometric freedom is affected; however, the texture given by the layered manufacturing process can be a way to investigate new aesthetic possibilities [7, 8]. To explore these, new materials must be developed, not only fulfilling 3DP properties, but filling sustainability and aesthetic gaps. Literature indicates that it is possible to create a new palette of materials for 3DP by adopting a more sustainable supply chain.

Construction and Demolition Waste (CDW) uses materials from demolitions or waste from new buildings that can enable this change [9]. Population growth and urbanization has contributed significantly to the increase of CDW [10]. Inadequate management of this waste has led to significant amounts of material being sent to landfills without any environmental concerns.

This chapter seeks to study and summarize the different compositions, dosages and materials used in the present mixtures for 3DP, as well as the inherent requirements

to successfully print them. To contribute to more sustainable mixtures, SCBA was considered as a supplementary cementitious material (SCM), and RBS was used to fully replace natural aggregates (sand), while allowing to achieve new aesthetic possibilities. Regarding the use of SCBA, several mortars were prepared, using different amounts of water depending on the percentages of SCBA incorporated. All mortars were subject to flow table and slump tests to assess flowability and buildability/shape retention, respectively. After that, some specimens of the produced mortars were moulded to evaluate their mechanical resistance, namely compressive and flexural strength at 7 and 28 days. Regarding the mixtures with RBS, to achieve a 3D printable material with aesthetical concerns in mind, tests were conducted to evaluate colour pigments, workability, extrudability, and printability.

In the end, final pieces were extruded to validate the printability of the mortars developed with waste.

2 Literature Review

2.1 *Compositions and Dosages*

When conceiving a cementitious mortar for 3DP, good workability and printable performance must be guaranteed to assure the best printing conditions in the equipment adopted. The material must be extrudable, flowable, buildable, ensure good mechanical strength and proper setting time to spread a continuous filament of material through the printing nozzle [11].

In addition, plastic viscosity must be significant to prevent the segregation of aggregates. A high content of paste is required and coarse aggregates should not be included to reduce the chance of the extruder blocking during the extrusion process [12].

Cementitious mortars for 3DP have been studied for quite a long time by many researchers from different universities and companies. Even though most of them do not reveal the exact composition of their mortars since their formulas are unique, it was possible to figure out some dosages of different 3D printable cementitious mortars during this literature review. The results can be seen in Table 1.

After collecting the above-mentioned information, it was possible to determine a proper mortar dosage (Fig. 1) for future 3D printable cementitious mortars based on the average of the compositions.

Additions include silica fume, fly ash and limestone filler, often used within the study of 3D printable cementitious mortars to reduce the amount of cement. Plasticizers, superplasticizers, retarders and accelerators are also present in some compositions [13, 15–18, 22].

It should be also noted that plasticizers/superplasticizers from Table 1 have not been included in the average values from Fig. 1, since they usually comprise a very

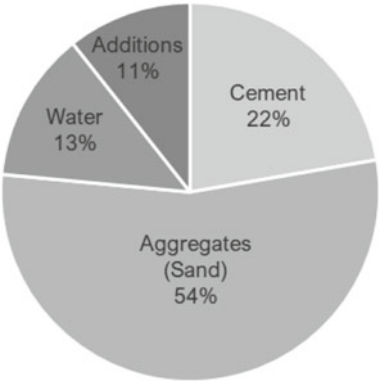
Table 1 Dosages of 3D printable cementitious mortars

Reference	Dosages							
	Cement (%)	Water (%)	SF ^a (%)	FA ^b (%)	LF ^c (%)	Sand (%)	P/SP ^d (%)	W/C ^e
Khoshnevis [13]	37.10	18.80	—	—	—	41.00	3.10	0.51
Tay et al. [14]	21.90	15.50	3.10	6.30	—	53.20	—	0.71
Nerella et al. [15]	19.50	8.10	8.10	7.70	—	56.10	0.50	0.42
Kruger et al. [16]	25.50	11.50	3.70	7.30	—	51.50	0.50	0.46
Kazemian et al. [17]	24.35	11.70	2.70	—	—	61.20	0.05	0.48
Schröfl et al. [18]	16.80	5.95	9.20	9.20	—	58.40	0.45	0.35
Teixeira et al. [19]	15.10	10.90	—	—	13.15	60.85	—	0.72
	10.70	11.10	—	5.70	10.70	61.80	—	1.04
Lafhaj et al. [20]	35.00	13.00	—	—	—	52.00	—	0.38
Ting et al. [21]	25.00	21.40	3.60	7.10	—	42.90	—	0.86
Paul et al. [22]	13.10	12.85	6.55	12.55	—	54.65	0.30	0.98

^aSF—Silica fume; ^bFA—Fly ash; ^cLF—Limestone filler; ^dP—Plasticizer; ^dSP—Superplasticizer; ^eW/C—Water/Cement ratio

Fig. 1 Average values for 3D printable cementitious mortars (from Table 1).

Source The Authors



small percentage of the mortars (1%–2%) and were not used in this experimental program.

It will later become clear that an optimal mixture for extrusion is hard to reach; it requires several tests and is dependent on the differences between the extrusion systems, the nature of the constituents, the equipment operator and the research purpose [23].

2.2 *Fresh and Hardened State Requirements*

When designing 3DPM, important requirements of the mixture in the fresh state must be satisfied, more precisely (adapted from Lim et al. [24]; Ma et al. [11, 25]):

- *Flowability/pumpability*: capacity of the paste to be smoothly transported from the mixer to the printing nozzle. It is affected by temperature and relative humidity;
- *Extrudability*: capacity of the material to continuously flow through the small pipes and the extrusion nozzle, without blocking the system or interrupting the filament;
- *Buildability/shape retention*: capacity of the cementitious material to retain its extruded shape and resistance throughout the early ages, under self-weight and under the pressure from upper layers, without excessive deformation. A good buildability is achievable when using high content of fine aggregates;
- *Open time*: time interval in which the fresh materials maintain a consistent flow rate for good extrudability. It is related to the change of flowability with time. The use of appropriate retarders can help control the open time.

On the other hand, the hardened properties required for printable materials are (adapted from Le et al. [26]; Buswell et al. [27]; Li et al. [28]):

- *Interlayer adhesion*: bond between two adjacent layers must be high to improve the structural integrity of the piece;
- *Drying shrinkage*: due to the inexistence of formwork, the surface area that is in contact with the air is considerable, allowing a high rate of water evaporation and accelerating drying shrinkage. This phenomenon increases the risk of cracking;
- *Mechanical strength*: the 3D printable materials must meet mechanical strength properties, namely compressive strength (tested at 3, 14 and 28 days), flexural strength (tested at 7 days) and tensile bond strength between layers;
- *Printability*: when the material reaches all the desirable fresh and hardened properties, a suitable 3D printable material is achieved.

As for the printing process, other relevant factors that influence the quality of the printed samples were collected from the literature (adapted from Bos et al. [29] and Rushing et al. [12]):

- *Printing system size*;
- *Robot speed and mobility*;

- *Flow rate;*
- *Pump pressure;*
- *Environmental conditions (temperature and relative humidity);*
- *Interlayer interval time;*
- *Print head speed;*
- *Print nozzle height and geometry;*
- *Surface dehydration;*
- *Layer height.*

It is also essential to look beyond the material properties and the printing process requirements when designing a 3D printable material, since there are other independent factors related to the final product that must be taken into account to guarantee its quality:

- *Structural performance;*
- *Thermal and acoustic insulation;*
- *Fire resistance;*
- *Permeability;*
- *Durability.*

2.3 Cementitious Mortars with Alternative Materials

Since 3DPM normally contains high amounts of cement [29], alternative SCMs have been considered, due to the high carbon emissions and energy consumption related to cement's manufacture. A modest replacement of cement has the capacity to increase the overall environmental sustainability [30]. Furthermore, the integration of these additives in 3DPM is also performed to improve the rheology of mortars and to achieve a proper buildability, for example [30, 31], as will be seen below.

Rice Husk Ash (RHA)

There have been recent studies about the use of rice husk ash (RHA) in this field. RHA results from the combustion of rice husk and presents a high amount of amorphous silica content and capacity of improving compressive strength, reducing porosity, and providing resistance against sulphate and acid attacks of the cementitious mortar. Therefore, it has been used to replace some percentage of cement, reducing carbon emissions [30].

For this study, the composition of the mixture was the common denominator: cement and RHA, silica sand, a superplasticizer and water. An extrusion-based technique was used to print it. After testing was done, the compressive strength of the mortar with RHA was 180–500% higher than the conventional mortar. Also, this cementitious mortar reaches the desired workability quicker than the conventional one [30].

Replacing 20% of cement with RHA is enough to reduce the material's cost substantially, while increasing the overall environmental sustainability of 3DP in Construction [30].

Recycled Glass

The growth of the applications of glass has been significant and with it, the rate of waste has increased significantly. Glass is a non-biodegradable material that is not suitable for landfill, therefore having major environmental impact. Thus, glass waste is commonly recycled and recovered to produce new glass products, which reduces its harmful effects [32].

Its application within 3DPM can take the form of fine glass powder as an alternative SCMs, reducing the use of cement [33]. However, these recycled glass aggregates may cause cracks and deplete the structural capacity of concrete, due to the alkali-silica reaction [32].

Two mixtures (one with PC, SF, FA, water and river sand and another with the same composition and recycled glass instead of river sand) were printed and then submitted to compressive, flexural, and splitting tensile tests [21].

A comparison between them showed that the recycled glass aggregate concrete had better flowing properties, due to its lower water absorption capacity and its smooth surface. However, it presented lower buildability. As for its mechanical properties, this mixture showed lower compressive, flexural and splitting tensile strength than the one with river sand aggregates, due to the weak adhesive strength between the recycled glass particles and the cementitious mortar [21].

In order to optimize the weak mechanical strength and poor buildability of the recycled glass concrete, there is a need to study the combination of the two aggregates in the same mixture, at different ratios, and the addition of accelerator and fillers (clay) capable of increasing thixotropy [21].

Magnesium Oxide Cement (MOC)

Another approach to reduce the use of PC in 3DP was proposed by Khalil et al. [31] who studied the possibility of incorporating reactive magnesium oxide cement (MOC), a sustainable replacement that can absorb CO₂ and promote strength gain.

The 3DPM is composed by reactive MOC as the SCM (54%); standard sand to improve the workability (6%); caustic magnesium oxide (cMgO) to provide good buildability (3%); magnesium acetate aqueous solution to maintain the W/C ratio (36%); polycarboxylate ether (superplasticizer) to reduce the plastic viscosity and preserve the flow consistency (0.4%); hydroxyethyl-cellulose (suspension-aid additive) to keep the mixture homogeneity during the printing process (0.3%); and non-ionic surfactant (defoamer) to prevent air entrapment into the mortar [31].

After some tests, this reactive magnesium cement mixture showed excellent extrudability, flowability and buildability, without any flow interruption or collapse, maintaining its initial shape. Due to the porous nature of the mortar, the printed specimens presented higher values of compressive strength when compared with the ones in cast, showing great potential as a 3D printable construction sustainable material [31].

Sugarcane Bagasse Ash (SCBA)

Several researchers have also been studying the possibility of introducing agricultural waste materials, such as RHA, wheat straw ash and SCBA in cementitious mortars.

Sugarcane is one of the main crops produced worldwide, with Brazil and India as the world's leading producers. The composition of a certain SCBA sample varies according to the planting location, crop, type of soil and groundwater [34].

As for the SCBA production process, the sugarcane is firstly crushed in sugar factories to extract its juice. The remaining fibrous matter is known as bagasse. The bagasse is being used nowadays as a biomass fuel in boilers for power generation in sugar factories [35]. The bagasse is then burned, resulting in the aforementioned bagasse ash. It is composed of fine burnt and coarse unburnt particles, which are deposited in the cogeneration plant [36] and makes it usable as soil fertilizer or filling material. However, most of the times, it is dumped in ash ponds or disposed in landfills [35, 37].

For some time now, many researchers have been studying the potential of SCBA to replace cement in mortars and concrete. Ganesan et al. [38] explored the effects of SCBA as a partial replacement of cement, concluding that with an optimum replacement of 20% of cement, there was a development of high early strength, a reduction in water permeability and a significant resistance to chloride permeation and diffusion. Quedou et al. [35] and Chi [39] concluded that a 10% replacement of cement with SCBA was the optimal limit, since it showed a superior performance on compressive strength, drying shrinkage, water absorption, initial surface absorption and chloride ion penetration (56 days), while contributing to the preservation of the environment.

To understand how the SCBA is used, several cementitious mixtures with SCBA in different ratios were grouped (Table 2).

Although Table 2 refers to cast/moulded specimens, the information summarized allowed to identify important insights for the composition of the first mixtures:

- The W/C ratio varies between 0.50 and 0.60, for mortars and concrete. It is higher with the increase of SCBA, since it consumes more water as it is lighter than cement [42];
- The percentage of SCBA incorporated is similar from mixture to mixture, assuming that, for these values, the mixtures kept or improved most of their relevant properties;
- Greater attention should be paid to the ones that do not contain coarse aggregates [39–41], since 3D printable cementitious mortars can only incorporate fine aggregates, due to the extrusion nozzle diameter.

In the next Sect. 3, tests of 3DPM where SCBA is incorporated will be demonstrated.

Table 2 Compositions and dosages of different mixtures containing SCBA

Mixture	Reference	SCBA (%)	W/C or W/(C + BA ^a)	Dosages (kg)				
				Water	Cement	SCBA	Fine aggregate (sand)	Coarse aggregate
Hardened concrete	Ganesan et al. [38]	0	0.53	203.00	383.00	0.00	575.00	1150.00
		5			364.00	19.00		
		10			345.00	38.00		
		15			326.00	57.00		
		20			306.00	77.00		
Sustainable concrete	Quedou et al. [35]	0	0.57	176.50	308.00	0.00	1010.00	932.00
		5	0.61	187.70	292.60	15.40		
		10	0.62	192.00	277.20	30.80		
		15	0.64	197.90	261.80	46.20		
		20	0.67	206.90	246.40	61.60		
Mortar	Chi [39]	0	0.55	288.10	523.80	0.00	1440.40	–
		10	0.50	264.30	480.60	53.40	1468.60	
		20	0.44	239.70	435.70	108.90	1497.90	
		30	0.39	214.00	389.00	166.70	1528.30	
Mortar	Arenas-Piedrahita et al. [40]	0	0.60	266.90	444.90	0.00	1557.20	–
		10		265.10	397.70	44.20	1546.90	
		20		263.40	351.20	87.80	1536.80	
Mortar	Arif et al. [41]	0	0.50	225.00	450.00	0.00	1350.00	–
		5	0.52	235.00	427.50	22.50		
		10	0.54	243.00	405.00	45.00		
		15	0.57	256.00	382.50	67.50		
		20	0.60	268.00	360.00	90.00		

^aBA—Bagasse Ash

Recycled Brick Sand (RBS)

Simultaneously, attention should be paid to the potential use of CDW, mostly disposed in landfills. However, as CDW is composed of several materials with different characteristics, each of them will be reused differently [9]. Its recycling process begins by crushing the material, with a reduced granulometry, achieving the form of aggregate (recycled aggregate). Recycled aggregates are a great alternative to natural aggregates in mortars, such as sand and gravel (the last one is not used in 3DP). This substitution and recycling process costs less than conventional aggregates and prevents the use of virgin materials [43].

Brick is one of this kind of waste and has been studied recently. For example, Adamson et al. [44] analysed the impact on concrete, with the partial replacement of

natural aggregates with crushed brick. Several conclusions could be drawn from this research: (i) brick aggregates showed higher porosity and absorptivity than natural aggregates; (ii) concrete with brick aggregates showed increased workability; and (iii) brick aggregates showed a slight improvement in compressive strength. In Sect. 4, a series of tests in which RBS was incorporated into mixtures for 3DP will be presented.

3 The Use of SCBA as a Partial Cement Substitute

In order to understand the potential of using SCBA and brick waste in the construction industry, two further studies were conducted.

3.1 *Materials and Methods*

Despite being very preliminary, this study aims at evaluating the use of SCBA as a partial substitute for cement in mixtures for 3DP, making them more sustainable.

The bagasse ash was collected from different waste disposals in Brazil and the sample used is a mixture of all the samples gathered from different waste disposals. PC (CEM I 42.5 R) was used for the trials in line with EN 197-1: 2011 [45]. As natural fine aggregates, two sands with different granulometries were used: 0–2 mm and 0–4 mm. According to Teixeira et al. [19], the extruder diameter may be up to five times larger than the maximum aggregate size. Since the extruder has a diameter close to 20 mm, it was possible to use sand with a particle size up to 4 mm. Since LF enables a better particle size distribution by filling the voids in the mixture and improves its mechanical strength, a small portion was also considered in the composition of the mortars. Tap water was added.

After creating several dosages with the necessary fresh state requirements to be printed, a manual extrusion system developed during the ADIMAQ project for plasters extrusion and optimized by Teixeira [8] for 3D printable cementitious materials was used in conjunction with an automatic gantry printer. The extruder works with a mechanical piston pushing the material through the extruder. Figure 2 shows the extrusion system used for the printing trials.

3.2 *Mortar Design*

Since the purpose of this work was to study the effect of SCBA on the composition of 3D printable cementitious mortars, small increments of this residue were tested (5, 10, 15, 20 and 25%), allowing a reduction in the amount of cement.

Fig. 2 Extrusion system.*Source* The Authors

The dosages of each constituent were based on the averages from Fig. 1 and on the experimental work proposed by Teixeira et al. [19], calculated for an approximate volume of 1 L. The different compositions and dosages are shown in Table 3.

The cement-SCBA replacement ratio is directly linked to its volume, not to its mass. For instance, if the volume of cement is 9% for 0% SCBA, the volume of SCBA that will need to be used for a 10% replacement will be 0.9%, so the correspondent volume of cement for this new mixture must be 8.1%.

The mixture dosages were controlled by water/powders (W/P) ratio, since it controls the fresh properties of the mortars, while W/C is responsible for their mechanical resistance. The proportions of the other constituents were not modified throughout the mixtures, apart from water, which was adjusted upwards whenever the percentage of SCBA increased.

The average values of the designed mixtures were compared with the average values from the literature shown in Fig. 1. The results can be seen in Table 4.

Table 4 shows that the mixtures prepared during the experimental work presented similar values to the ones set forth by other authors. The greatest variation found in the dosages was related to the percentage of cement used. Its reduction is linked to the high quantity of sand used that fills with paste the void between the particles [19].

It was also possible to devise a graph showing the variation in the water content according to the variation in the amount of SCBA used (Fig. 3), which is close to a quadratic function ($R^2 = 0.9818$). With this, it was possible to estimate the necessary water for the following mixtures (20% SCBA and 25% SCBA), avoiding adding more water than necessary.

Table 3 Compositions and dosages of different mixtures containing SCBA

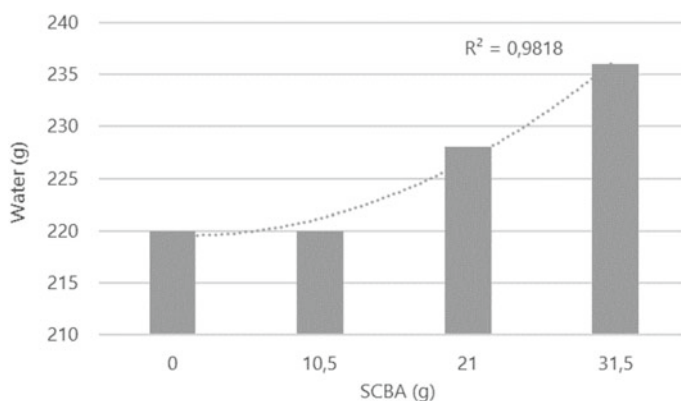
Mixture reference	% of substitution (volume)	PC (%)	LF (%)	SCBA (%)	Water (%)	Sand 0–2 mm (%)	Sand 0–4 mm (%)	W/C	W/P ^a
SCBA-0	0	13.50	11.80	0.00	10.70	6.40	57.60	0.79	0.42
SCBA-5	5	12.90	11.80	0.50	10.70	6.40	57.70	0.83	0.42
SCBA-10	10	12.20	11.80	1.00	11.10	6.40	57.60	0.91	0.44
SCBA-15	15	11.50	11.80	1.50	11.40	6.40	57.40	1.00	0.46
SCBA-20	20	10.80	11.70	2.00	11.80	6.40	57.30	1.10	0.48
SCBA-25	25	10.10	11.70	2.50	12.10	6.40	57.20	1.20	0.50

^aW/P—Water/powders ratio (powders include cement, LF and SCBA)

Table 4 Comparison between the average values of the mixtures from literature and experimental work

Mixture constituents	Cement (%)	Additions ^a (%)	Water (%)	Sand (%)
Average values from literature (Fig. 1)	22	11	13	54
Average values from experimental work (Table 3)	12	13	11	64

^aAdditions include SF and FA (literature dosages), SCBA and LF (experimental work)

**Fig. 3** Water used as a function of incorporated SCBA. *Source* The Authors

3.3 Laboratory Tests

Bulk Density of SCBA

The bulk density, ρ , represents the mass of a given material divided by its total volume and depends on the percentage of existing voids. Before setting up any mixture, it was necessary to collect the bulk densities of all the components to estimate their amount in each mixture. Since the bulk density of each material had already been calculated in a previous study [19], the SCBA's were the only element to be determined. The results are shown in Table 5.

SCBA's bulk density was determined through the pycnometer method, as described in NP EN 1097-7:2012 [46]. It is presented in Fig. 4.

Table 5 Bulk density of each component

Component	PC	SCBA	LF	Sand 0–4 mm	Sand 0–2 mm
Bulk density (kg/m ³)	3100	2330	2700	2637	2636

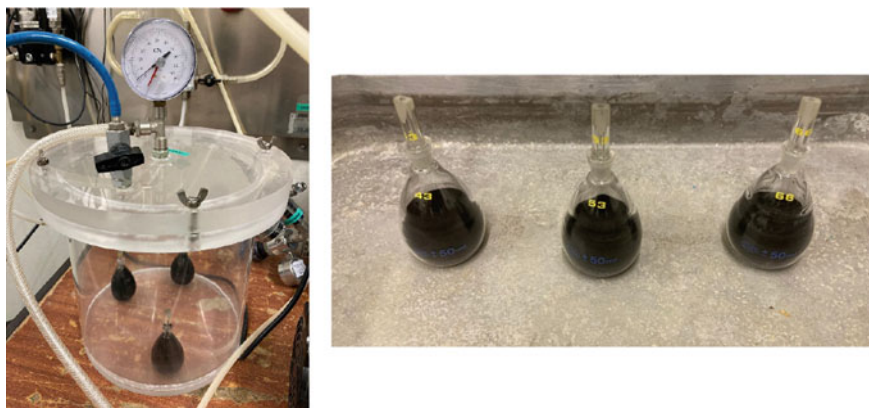


Fig. 4 Determination of SCBA's bulk density with pycnometers. *Source* The Authors

Particle Size Distribution of SCBA

Since the activity of SCBA highly depends on its particle size and fineness, the size distribution of the sample's particles was determined. This test enables a significant understanding of the effectiveness of a certain material, since some of its properties (bulk density, permeability, etc.) are controlled by the size of the material's particles.

The test was conducted according to the procedures described in NP EN 933-1:2014 [47] and consists of the division and separation, by means of a set of sieves, as shown in Fig. 5 (left), of a material in different particle size classes of decreasing granulometry (4 mm; 2 mm; 1 mm; 0.50 mm; 0.250 mm; 0.125 mm; 0.063 mm). The adopted method starts by sieving with washing (to remove the particles smaller than 0.063 mm and dust) followed by dry sieving.



Fig. 5 Sieve column and shaker (left), and particle size distribution (right), from top-left to bottom-right: 1 mm; 0.50 mm; 0.250 mm; 0.125 mm; 0.063 mm; <0.063 mm. *Source* The Authors

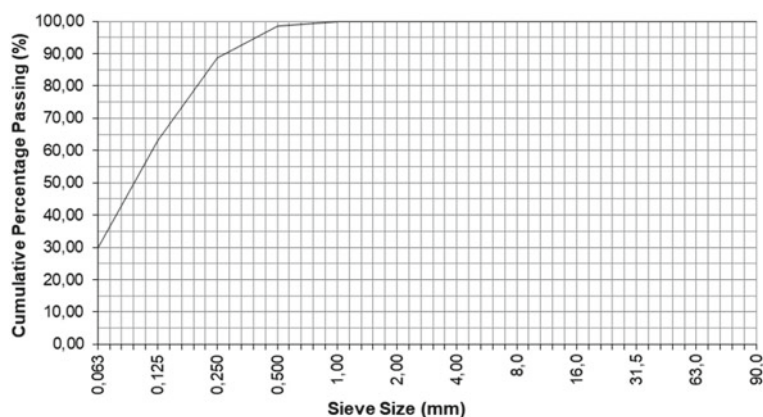


Fig. 6 SCBA's granulometric curve. *Source* The Authors

After this, the material retained on the sieve with the largest aperture was weighed, followed by the others with a smaller aperture. The percentage of material on each sieve was calculated according to the mass retained in each and the initial mass of the total sample, which allowed the graph presented below to be drawn.

According to Fig. 6, almost all the material cross the 0.500 mm sieve. However, only 30% of the sample went through the 0.063 mm one, which means that a very small percentage of it has a cement-like fineness (the size of cement's particles is usually $< 0,1$ mm). To avoid significant losses of material (in the order of 70%), the one that went through the 0.250 mm sieve was the one used, allowing the removal of coarse material.

Consistency of Fresh Mortar

After calculating the dosages, the mixtures were prepared, so as to assess the need to add water or any other materials, according to the intended purpose of the mortars (in this case, for 3DP).

The powders were initially deposited in the bowl, together with $\frac{3}{4}$ of water, and then blended for 1 min to obtain a uniform mixture (Fig. 7). Then, the remaining water was added ($\frac{1}{4}$) and the mixture was stirred for 1 more minute. There was a short pause for cleaning the mixer blade to prevent jamming. The mixture was then blended for 2 extra minutes and poured in the flow table.

The determination of the mortars' consistency in fresh state by the flow table method was based on EN 1015-3:1999 [48]. The mould was first filled with two layers of mortar that was compacted through 10 short strokes with a tamper. After that, the mould was removed and the slump, defined as the displacement suffered by the mortar when the mould is removed, was measured (Fig. 8 (left)). Then, the material was jolted 15 times on the flow table and the spread mortar diameter was measured in two perpendicular directions (Fig. 8 (right)). The average diameter

Fig. 7 Placement of the constituents in the container (left) and constituent mixture (right). *Source* The Authors



Fig. 8 Evaluation of mortar’s slump (left) and mortar’s flow (right). *Source* The Authors



represents the flow value in mm. The flow values obtained for each mixture are shown in Table 6.

Based on previous studies to obtain a suitable flowability of the mixture for 3DP, flow values should fluctuate between 175 and 210 mm [23]. Since the flow value of the reference mixture (SCBA-0) was 168.5 mm, the other values should oscillate between ± 10 mm, according to NP EN 450-1:2012 [49]. As seen in Table 6, to obtain values within that interval, more water was added whenever the percentage of SCBA was increased.

As for the slump test, all mixtures showed results close to zero, as intended. The material must guarantee shape stability after the extrusion due to the lack of support formwork to sustain the weight of the upper layers [50].

Table 6 Flow table test results

Mixture reference	SCBA-0	SCBA-5	SCBA-10	SCBA-15	SCBA-20	SCBA-25
W/P	0.42	0.42	0.44	0.46	0.48	0.50
Flow (mm)	168.50	174.00	170.00	172.50	176.00	181.50

Compressive and Flexural Strength of Cast Specimens

The compressive and flexural strength tests were performed based on EN 196-1:2016 [51]. After determining the consistency, the fresh mortar was poured into a specific mould with three slots, so that three test specimens could be obtained per mixture. The specimens were stored in the mould in a moist atmosphere for 24 h, then demoulded and stored under water until being subjected to mechanical strength tests. At the required times (7 and 28 days), the specimens were subjected to a flexure strength test, and then each half went through the compressive strength test (Fig. 9). The results can be seen in Table 7.

A decrease in the mechanical properties of the mortars was expected when the amount of SCBA was increased since it does not provide a similar strength to cement. The increased amount of water added (W/C values close to 1), on the other hand, also had its impact on the results.

Fig. 9 Flexural (left) and compressive (right) strength tests. *Source* The Authors

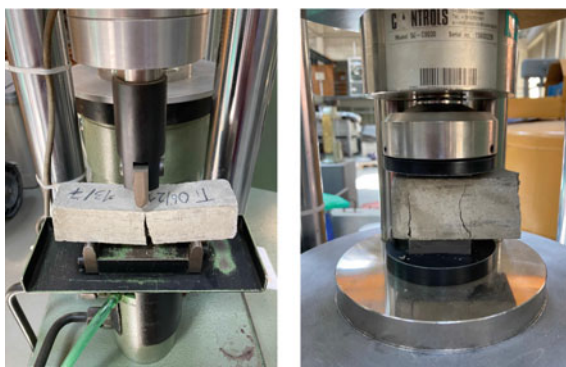


Table 7 Mechanical resistance of cast specimens

Mixture reference	Average flexural strength (MPa)		Average compressive strength (MPa)	
	7 days	28 days	7 days	28 days
SCBA-0	5.30	5.90	30.40	35.00
SCBA-5	4.60	5.80	27.50	33.20
SCBA-10	4.50	5.20	24.10	28.60
SCBA-15	3.90	4.80	18.90	23.70
SCBA-20	3.70	–	16.60	–
SCBA-25	3.00	–	14.20	–

Fig. 10 Printing trial of the composition with 15% SCBA. *Source* The Authors



3.4 Extrusion Test

A first trial was carried out using a composition with 15% of SCBA to assess its effect on printable materials. The printed specimen has an average layer width of 35 mm and a layer thickness of approximately 15 mm.

As seen in Fig. 10, the prototype presented an adequate buildability (retained its shape after extrusion, while supporting the weight of the upper layers) and the extrusion process occurred continuously without clogging the printing system, meaning that the mixture had enough flowability to be extruded. However, it is clear that the material is too dry, which resulted in the appearance of some voids and roughness in the sample's surface. This problem may be related to the significant reduction in the amount of cement at the expense of SCBA, which can result in segregation. Thus, it can be concluded that the following mixtures that need to go through testing will be those at 5% and 10% SCBA.

4 The Use of RBS as a Substitute for Natural Aggregates

4.1 Materials and Methods

The purpose of this study was to completely replace the natural aggregates (river sand) with RBS, with a maximum aggregate size of 4 mm. In addition to replacing a natural raw material, there was an attempt to explore the aesthetic possibilities of 3DPM with this waste material. The brick aggregates resulted from the debris of clay bricks, as will be explained in Sects. 4.3 and 4.5. White PC (CEM II/B-L 32.5R) was used as binder.

Table 8 Materials used in the mixture compositions tested

Mixture reference	Brick (total wt%)	Brick (solids wt%)	White cement (total wt%)	White cement (solids wt%)	Water (total wt%)	W/C
1	0	0	71	100	29	0.70
2	7	10	60	90	33	0.89
3	13	20	50	80	37	0.75
4^a	20	30	47	70	33	0.71
5^a	27	40	40	60	33	0.67
6^a	36	50	36	50	28	1.00
7	40	60	27	40	33	1.25
8	44	70	19	30	37	2.00
9	45	80	11	20	44	2.50
10	43	90	6	10	41	4.00

^aExtrudable mixtures

4.2 Mortar Design

The extrudability of the material was tested with a gradual reduction in the percentage of cement in the 3DPM. The goal was to reduce PC as much as possible and understand the advantages and drawbacks of the extrudability and the final material colour variation. The materials of the compositions tested are presented in Table 8 and Fig. 14 presents the colours obtained. It was only possible to extrude the material in tests 4, 5 and 6. For tests 1, 2 and 3 the filament, despite being extruded, was too fluid, while in tests 7 to 10 there was a clear lack of binding due to the high level of segregation. So, it can be concluded that the mixture should have at least 50% cement (mortar 6) and at least 30% of brick sand (mortar 4) to be extruded. It was thus considered that the ideal scenario for a future printing trial would be to use 60% cement and 40% brick, with a W/C ratio of 0.67 (mortar 5).

4.3 Laboratory Tests

Particle Size Distribution and Crushing of RBS

The particle size distribution of the sample was also determined (Fig. 11), since the granulometry of the CDW influences the final mortar. This test effectively controls some material properties such as bulk density, permeability, etc. The experimental test also followed the procedures described in NP EN 933-1:2014 [47].

Figure 12 (left) shows the granulometric curve obtained after sieving, as well as the final aspect of the RBS. The procedures carried out to obtain RBS are described below:

Fig. 11 Sieve column and shaker (left), sieving with washing (right) and particle size distribution (bottom).
Source The Authors

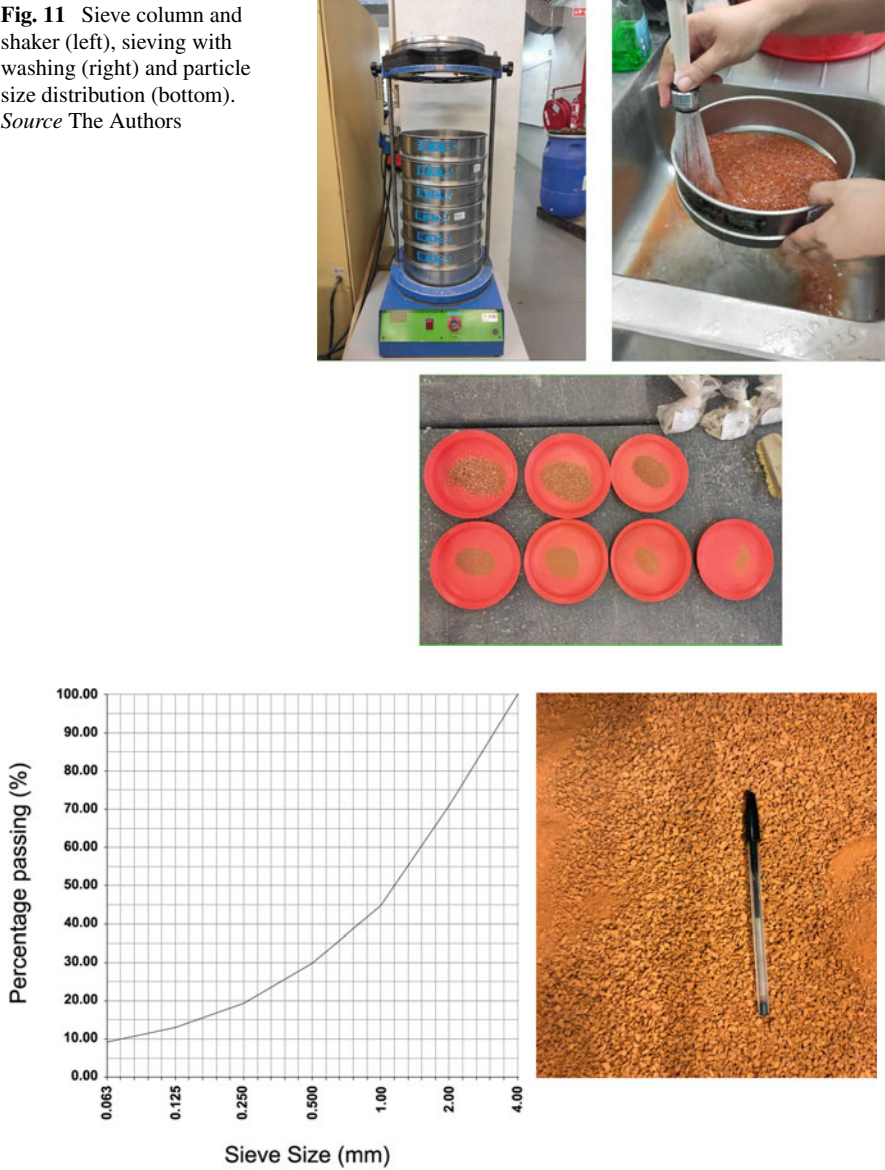


Fig. 12 Granulometric curve (left) and RBS (right). *Source* The Authors

Fig. 13 Manual extrusion test with a hand syringe (baker's tube). *Source* The Authors



- (i) the brick was manually crushed with a hammer and placed into a crusher with the jaws positioned 4 mm apart;
- (ii) after all the material went through the crusher, it was filtered using a 4.75 mm sieve;
- (iii) the larger fragments were crushed again, with the crusher jaws 2 mm apart;
- (iv) after this second round, the material was sieved again using the 4.75 mm sieve, and crushed one last time with the crusher jaws positioned 0 mm apart;
- (v) finally, all the material was sieved through a 4 mm sieve and the respective granulometric curve was plotted according to NP EN 1097-6 [52].

Manual Extrusion Tests

After brick sand preparation, tests with a hand syringe (baker's tube) were carried out to understand if it would be possible to extrude the material, and what would be the minimum amount of cement needed for a good extrudability (Fig. 13).

Colour Tests

Following aesthetic concerns, a chromatic pallet was put together to show the colour possibilities provided by the two main components: cement and brick sand. The results observed in Fig. 14 are related to the compositions presented in Table 8.

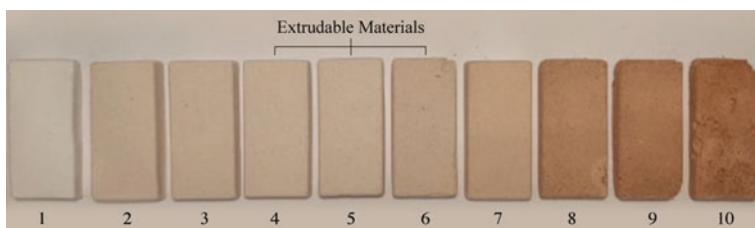


Fig. 14 Colour of the mixture compositions tested. *Source* The Authors

Fig. 15 Constituent mixer.

Source The Authors



Consistency of Fresh Mortar

After calculating the dosages, the mixture for printing was prepared to assess the need for water or other materials.

The materials (brick sand, cement and water) were poured into the bowl at the same time, gradually, so that the mortar would not get too thick and would not jam the mixing paddle. Throughout the process, the amount of water was added cautiously to avoid the mixture being too loose (Fig. 15).

4.4 3D Model Design

This stage required several steps because the system had not been thoroughly prepared for 3DP with cementitious mortars. To begin with, a 3D model was obtained using the *Tinkercad* software, a free online 3D CAD software. The piece geometry was inspired by the Alvar Aalto vase (*Savoy Vase*) (Fig. 16 (left)). Then, *Ultimaker Cura*, a slicing software made for FDM 3D printers, was used in order to transform the 3D model into a path that could be read by the printer (G-code). Despite being a good solution for polymeric materials when used with cementitious materials, some problems can be observed regarding printing definition and material's properties (Fig. 16 (centre)). After obtaining the G-code file, a manual edition was done to make sure the extruder starts and finishes the printing process in the same place. This ensures the material is extruded under the same conditions throughout the part. To confirm that the editing of the G-code had been done correctly, the software *CAMotics* was used to simulate the 3DP (Fig. 16 (right)). Finally, the printing speed and the nozzle height were stabilised (speed: 100 mm/s; nozzle height: 15 mm in the first layer, decreased to 10 mm in the following layers).

4.5 Extrusion Test

To print the final object (Fig. 17), the composition with the best results in manual extrusion tests was used as the base composition. However, adjustments were made in adapting the material to the automated 3DP system (Table 9). The final composition was similar to composition 5; but the water content could be reduced by 10% due to an increase in the extrusion pressure provided by the mechanical extruder. This material optimization is suggested by Ma et al. [25].

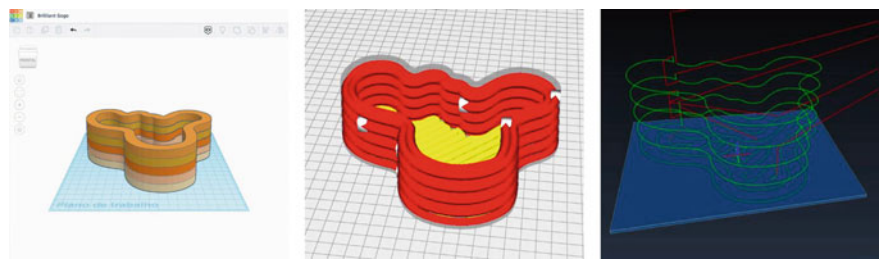


Fig. 16 Procedure performed during 3DP stage: *Tinkercad* modelling (left); slicing in *Ultimaker Cura* software (centre); and g-code edition assisted by *CAMotics* (right). *Source* The Authors

Fig. 17 Extrusion test (left) and final printed piece (right). *Source* The Authors



Table 9 Final 3DPM composition used in an automated system

Test	Brick (total wt%)	Brick (solids wt%)	White cement (total wt%)	White cement (solids wt%)	Water (total wt%)	W/C
Base (5)	27	40	40	60	33	0.67
Final	29	38	48	62	23	0.49

5 Conclusions

The study of SCMs is not new within the design of new 3D printable cement-based mortars, with additions such as SF and FA. However, despite using the abovementioned additions to improve important properties of these materials, most of the proposed compositions in the literature maintain their ratios of PC. This study sought to evaluate the effects of a further reduction in the amount of cement used in the developed 3D printable cementitious mortars, which is already low due to the significant quantity of sand and LF included in these mixtures, as opposed to the ones in the literature.

An increase in the amount of SCBA used in the mortars required a greater amount of water to maintain the desired levels of fluidity and slump, which decreased the mortars' mechanical performance. A condition which is probably related to the fine structure and lightness of the residue employed. For shape retention, and after the printing trial was evaluated, the slump test showed that figures nearing zero were ideal to produce a buildable 3DPM, while the flow test demonstrated that figures close to 170 mm ensure an adequate flowability. A 15% substitution of cement by SCBA is not advisable due to the high number of voids and roughness in the sample. This problem can result in segregation, affecting the durability of the material.

The study related to the use of RBS intends to demonstrate the potential of residues, such as CDW, for the development of a new palette of materials for 3DP. Alongside SCBA, it contributes to the transition to a more sustainable supply chain, avoiding the destruction of riverbeds by the extraction of river sand. Besides, by using CDW such as brick sand, with chromatic possibilities, the aesthetical possibilities in 3DP in Construction are increased. Several colours were achieved by including this aggregate in white cement; however, only three compositions were extrudable and printable.

Even though the first results were positive and motivating, further printing trials should be conducted not only to obtain a visually appealing piece, but also to understand the best replacement ratios for both mortars and maximize their performance in their fresh and hardened states, i.e., their rheology and mechanical strength.

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4D Printing and Construction: Reality, Future, or Science Fiction?



Jorge Lino Alves , Leonardo Santana , and Bárbara Rangel 

Abstract 4D Printing is the combination of traditional additive processes with smart materials and external stimuli. This combination guarantees the printed parts the ability to transform themselves over time, which could be, for example, self-sensitive, self-assembly, or self-healing. These skills can be of great interest for modern constructions, as the world is demanding autonomous structures, with low energy consumption and environmental impacts. In this sense, this study sought to analyze the movements of 4D printing in civil construction and architecture to understand how close, or distant, this technology is to the reality of these sectors. Results show that the 4D stage in these applications is still very embryonic and limited at laboratory scale. However, there is potential for the future, if major challenges such as the production of large parts and, mainly, the control of the transformations of the components produced and the external stimuli applied are overcome.

Keywords 4D printing · Change with time · Transformations · Construction · Architecture

1 Contextualization

Historically, the Neolithic Revolution, also known as the Agricultural Revolution, is considered an important step for humanity in establishing the social structures we have today. Until then, human beings were hunters and gatherers and were constantly walking around the world in search of supplies. With the mastery and development of agricultural techniques, associated with animal domestication and settlements, people began to live in communities and, therefore, settled down, starting a sedentary

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life. This new conjunction favored the development of architecture. Since human no longer needed to move around in search of food, man started to think about building shelters that were bigger, more resistant and comfortable [1–5].

The characteristics of the buildings varied according to the construction materials available, as well as the ideal, or traditions, of those who lived there, thus expressing their organization, worldview, relationship with the environment and manufacturing methods. Although different regions often share similar raw materials (wood, stone, mud, straw, leaves, adobe, among others), the aesthetic aspect of the work was distinguished from each other through the insertion of ornaments, colors and compositions that represented the culture of the people, that is, a unique identity responsible for diversity within a process known as architectural creativity [3, 6]. Vatan [3] describes in his work that traditional buildings and their respective manufacturing techniques are affected by local conditions, such as material properties, geographic position, soil, natural exposure and susceptibility to earthquakes, floods and climatic variations. However, according to this same publication, what makes an architecture unique is the way it is shaped by the traditions and beliefs of the community that constitute the culture itself.

Looking at history, it appears that architecture and construction are a direct reflection of the thinking and customs of a group of people. Thus, all evolution within this scenario, whether in the development of new materials or in the construction techniques, is a representation of the intellectual growth and capacity of human beings to express themselves. Advances in these areas are significant for human evolution and survival and, nowadays, are also a matter of market competitiveness.

Civil engineering and architecture clamor every day for the development of new building materials that meet current requirements like sustainability, durability, reliability, safety, low cost and weight, greater mechanical strength, flexibility for the use in extreme places and conditions and, of course, that are “eco-friendly”. Especially on the environmental issue, the cement industry (based on traditional Portland), the most common raw material in buildings, is responsible for high CO₂ emission rates, around 622 kg for each ton produced. This entire scenario of search for preservation and innovation has been open space to solutions such as geopolymeric concretes, fiber reinforced polymers, nanoadditivated cementitious composites, smart materials (self-sensitive and self-healing concrete, color-changing glass, shape memory elements, etc.), 3D graphene, laminated wood, translucent wood, hydroceramics, artificial spider silk, wool bricks, microbial cellulose, 3D printed bioplastics and many others [7–14].

Undoubtedly, the evolution within materials is something revolutionary that, consequently, becomes a direct factor for the development of new building techniques. However, the latter are more noticeable to the public than the material used on it, as it is enough to walk through the streets of a city to see how much more complex the works are in geometry and how quickly they appear overnight. Such advance in civil engineering is mainly related to a set of technologies, or ideas, known as “Modern Methods of Construction (MMC)”.

In the published literature it seems that there is no global, exact and accepted definition of the concept of MMC, however, the terminology converges to something

collective used to describe innovative building techniques, which deviate from traditional models, and which can be carried out both in the workplace, and outside it [15, 16]. Ofori-Kuragu and Osei-Kyei [17] synthesize the interpretation of MMC as a wide range of new technologies, techniques and materials used to enable continuous improvement in the processes and delivery of building products, through the application of lean theory for removal of waste and increase in value. MMCs represent the industrialization of construction, based on the implementation of prefabricated systems. These industrial processes are used in designing, planning, manufacturing, transporting and assembling components on-site [18].

The development of “Modern Methods of Construction” is seen as a heroic alternative to bring down the bad reputation around civil construction, related to delayed and overpriced projects, as well as to make up for the shortage of skills (hand of qualified work) and promote sustainability. In addition, every day the demand for rapid construction is increasing, whether it is a simple population growth, changes in customer preferences or more serious factors, such as post-war or post-environmental disasters crises [17, 19, 20].

The prefabricated technology appears, therefore, to professionalize this entire scenario, bringing civil construction into the manufacturing environment. Such factories will be able to produce it all: from structural elements to complete modules, that is, volumetric units (constructive section) fully supported and integrated with technical systems and with the appropriate finishes (coatings, lighting, among others)—which determines a high degree of pre-manufacturing. All this modernization has resulted in greater predictability of projects (construction is now carried out within a controlled space), an increase in quality control, minimization of production times and costs, safety for workers and the environment, and reduced impacts of building sites on its surroundings [21]. Among the main technologies related to MMCs, the following stand out: volumetric and semi-volume construction (modular or capsules), panel-based systems, hybrid techniques (volumetric combined with panels), flat slab construction, precast concrete foundations, among others [15, 19, 22].

It is undeniable that the manufacturing processes mentioned above are modern and contrast with manual construction based on laying bricks with mortar, winding iron structures, cutting, and nailing wood or positioning and fitting tiles. Now imagine a robot being able to deposit material and build slender walls, layer by layer, finishing a house in a matter of days or hours. Looking at it this way, doesn't it look like a scene from a science fiction movie? Or maybe that we are going to board a spaceship and go somewhere we could get a comfortable and safe shelter within two “clicks”? No need to go that far; 3D Printing, or Additive Manufacturing (AM), already builds houses and will, eventually, build yours!

The Fourth Industrial Revolution (4IR), also called Industry 4.0, presented us with an innovation scenario based on the concept of “digitalization”, which drives the connection between men and machines (technology), within an “intelligent factory”, through cyber-physical systems (CPS) [23]. This movement was characterized by advances in materials science and the emergence of tools such as Artificial Intelligence (AI), Internet of Things (IoT), autonomous vehicles, robotics, data analysis and Big Data, cloud computing, 3D printing and more [24, 25].

Although civil construction often resists to the adoption of innovative technologies, when compared to other industrial sectors, it was able to accept and apply the assumptions of Industry 4.0, in what came to be called “Construction 4.0”. Digitizing and industrializing construction processes are essential pillars to modernize the sector and promote gains in performance and labor, as well as reducing costs, expenditure on materials and energy consumption. The use of 3D Printing ensured that the objectives mentioned above were achieved by the most diverse industries, which motivated its application in civil construction as well [26, 27]. 3D printing is a promising process in the automation of civil construction, which makes works more economical, faster, more precise, complex and with less risk to the safety of the people involved [28, 29].

Let’s show the application of 3D Printing in civil construction in an example that directly affects the growth of a community: in education. In Malawi, Africa, the world’s first printed school was built. This initiative was carried out by the 14 Trees company, the joint venture between the CDC Group and the Holcim construction company, which used a large-scale printer (BOD2) Danish COBOD. The school walls, approximately 56 m², were built in 18 h. Malawi, according to UNICEF, needs about 36,000 classrooms, which at least, with traditional construction, could take up to 70 years to complete, according to 14 Tress. The company estimates that with 3D Printing technology this period, for the same number of classes, could be reduced to 10 years [30–32].

The school’s model joins a series of new projects in 3D Printing, such as concrete bridges, like the one built in Venice (Italy) [33], and metal, over the canals of Amsterdam [34]. However, the biggest escalation of this technology is seen in the construction of houses. The “Fibonacci House” in Canada has even been listed on the Airbnb real estate rental platform, consisting of a 35 m² structure made up of 20 printed parts, built in 11 days [35]. Another example is the Milestone Project in Eindhoven (Netherlands). The house made of 24 printed pieces in 120 h, with 94 m² of living area, is the first legally liveable model and has already been rented, that’s right, with people living in Europe [36, 37]. The evolutions in 3D printing of buildings do not stop here. We can already see two-story structures, such as the Kamp C project [38], and works that occupy large areas, including the largest in the world in Dubai, with 640 m² [39] (Fig. 1), and the military barracks in the United States ($\approx$ 353 m²) [40].

There are also more audacious projects, such as the TECLA, developed by Mario Cucinella Architects and the company WASP. The idea, whose prototype is already completed, seeks to integrate materials from the past with 3D Printing technology. Rounded houses were printed with earth from the construction site, mixed with rice fibers, water and a binder (something reminiscent of adobe). The creators say that the design of the houses can be adapted to the characteristics of the place where it will be implemented, in a sustainable way [42].

The entire context clearly shows the human evolution in the way of thinking about civil construction. The previous example of the earth house also shows 3D printing as a building innovation, however, without leaving aside the traditions and peculiarities of each location. We can say that 3D Printing is already a reality at the construction

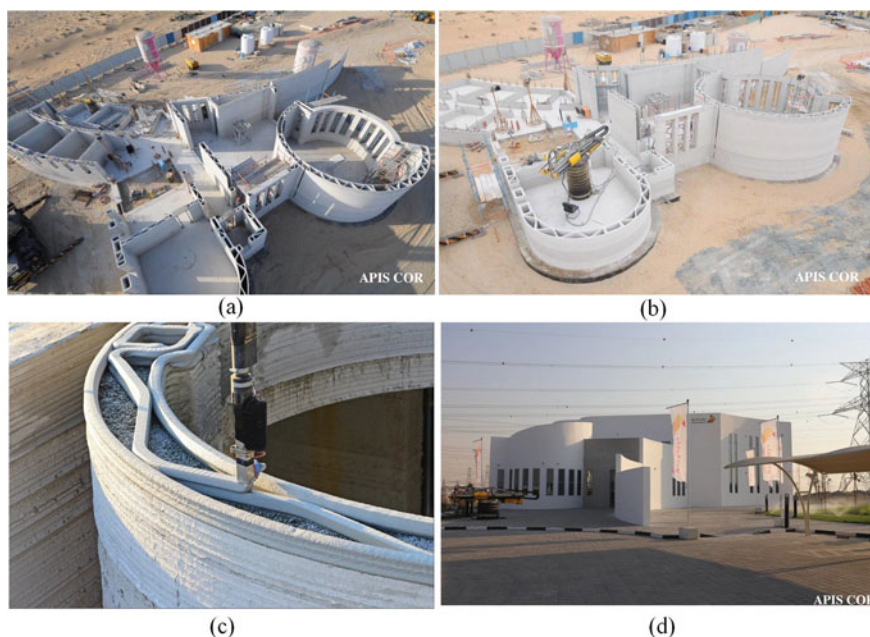


Fig. 1 Printing process (a), (b) (c), and finished building (d) (adapted from [41]). *Reprinted from [41] with permission from APIS COR*

site, once it has already been materialized, it is functional and has impacts on social and economic development.

In recent years, however, the scientific community has been presenting solutions that allow parts manufactured by 3D Printing the ability to transform themselves over time, within a concept called 4D Printing. Even though 3D printing is a reality in civil construction, as shown in the previous examples, many challenges are still reserved for the future of this technology in the sector, including project regulations in local engineering councils, attracting investment, developing machines and materials for large volumes of operation and, of course, user's acceptance. In this sense, would it be something megalomaniac to already think, for example, of building houses with self-assembly and self-healing skills? That's what we intend to explore in the next topics by mapping 4D technology in the field of civil engineering and architecture.

2 4D Printing

Technological evolution is in fact the threshold between the fear of the unknown and the fascination of discovery, which constantly imposes on people a process of adaptation to make them connected and competitive. 3D Printing is part of this social transformation since in today's world it is applied in several sectors that impact our

lives, such as the aerospace industry, automobile, food, medical, clothing, electronics, construction, among other areas, allowing the production of components hitherto difficult to obtain by traditional manufacturing methods [43–45]. According to data from Sculpteo [46], 25% of current 3D Printing applications are for personal interests, therefore showing how far these technologies are advancing into the domestic environment. However, as the world adapted to the revolution caused by 3D Printing, a new era appeared, 4D Printing [47].

4D Printing is described in the literature as a consequence of the rapid growth, and the interdisciplinarity, of research on smart materials, 3D printers and design methodologies [48]. First presented in 2013 by the MIT Self-Assembly Lab, the technology is an evolution of its 3D predecessor, in which one more dimension is added to allow the manufactured parts to be transformed over time, the latter being the fourth dimension [43, 47, 49, 50].

For a moment, we can imagine that 4D Printing uses new equipment and systems, however, it uses the same techniques and machines as its 3D predecessor does. Among the main AM techniques used in 4D Printing, the following stand out: Fused Filament Fabrication (FFF), Stereolithography, PolyJet™, Selective Laser Sintering (SLS), Direct Energy Deposition (DED) and Direct Ink Writing (DIW).

The difference between 3 and 4D printing lies in the nature of the raw material used. The latter uses smart materials such as polymers and metal alloys, and shape memory materials (SMPs and SMAs), liquid crystal elastomers, composite hydrogels, among others. These materials change their physical and chemical properties when receive an external stimulus (temperature, humidity, water, pH, magnetic field, etc.), allowing the parts to change, over time, in color, function, shape, self-assembly, production of electrical current or become bioactive. In summary, unlike 3D Printing in which the produced elements are static, in the 4D universe the components are dynamic and animated [48, 49, 51–58]—Fig. 2.

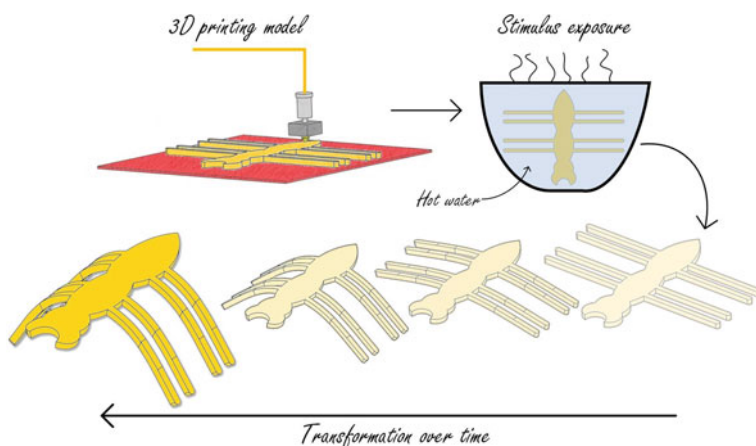


Fig. 2 4D printing schematics (Source The Authors)

In addition to 3D Printing technologies, materials and external stimuli, interaction mechanisms and mathematical modeling are also fundamental pillars for 4D Printing. The first is the process of programming the deformation of the material into a temporary form, while the second will define the distribution and structure necessary for the transformations to take place [59, 60].

Medicine is one of the most enthusiastic fields around 4D printing, involving the production of scaffolds, stents, sensors, drug delivery systems, implants, splints and even, for the future, organs; all this because the manufactured components can establish a dynamic relationship with the body, even following its growth [49, 61, 62]. The 4D technique is also explored in the printing of foods to make products that change their taste, color, shape and nutritional value as a function of stimuli such as pH, water absorption, microwave, temperature, among others [63, 64].

Alshahrani [57] also adds as potential 4D printing application areas the aeronautics and space industries, sports products, piping manufacture and civil construction. The last one, for example, can be revolutionized due to the ability of self-assembling parts manufactured in 4D. Parts too large to be built entirely by conventional 3D printers can now be compacted for manufacturing and then expanded for use [65, 66].

3 4D Printing in Civil Construction

4D Printing can be considered a technological concept still in its embryonic stage. Just think that 3D Printing, which has already gone through the transformation from a set of prototyping technologies to a group of manufacturing techniques, continues in a development process to assert itself in the manufacture of end-use products [58, 67]. As expected for an evolving technology, 4D Printing has challenges and limitations that are necessary to overcome for its full application, including:

- General questions: common questions facing a new technology in society. What is the immediate practical use of 4D Printing? How can 4D Printing be done? When will 4D Printing be able to leave the lab-only idea [57, 68, 69]? Despite being simple in essence, these questions are the most complex in practice, as they are responsible for breaking the suspicions and motivating investments, research teams and, mainly, potential fields of application;
- Materials and transformations: even with the recent developments in 4D Printing, there are still limitations regarding the mechanical characteristics and the control of material deformations [70]. It is necessary to understand how the deformations will behave due to the multiple transformation cycles of the parts, especially regarding the degradation of material properties [69]. Alshahrani [57] shows in his article that the literature needs to explain important issues about materials in the 4D scenario, such as: (i) the behavior when they are simultaneously exposed to more than one external stimulus; (ii) whether there is full recovery of shape or configuration when the stimulus is removed, and (iii) whether the inherent properties of the material change over time or remain constant. 4D Printing is

mostly based on polymer-based raw materials, which are commonly not very resistant to high thermal levels and have low glass transition temperatures. These particularities limit the range of application of the technology and restrict the types of stimuli that can be used to generate transformations in the manufactured components [57, 68, 71]. According to Ahmed et al. [58], there is also a challenge in 4D Printing that is linked to the interaction between smart materials and the 3D Printing technologies. The materials are often not compatible with the printing systems, which, according to the author, highlights the need to discover new solutions that can be directly processed by the available AM systems. Finally, the safety of structures manufactured with these programmable raw materials must be considered to avoid tragedies caused by an unexpected transformation, for example, that causes the collapse of a building [69];

- Design and technologies: the design for 4D Printing must be carried out to adapt to the specific conditions of the application environment, as this is the only way the product will be able to offer the expected results. The complexity of materials and designs for 4D makes building predictive algorithms about part transformations a difficult task. Therefore, the need for the creation and optimization of these computational tools grows because of the increase in the quality and precision of the elements produced by 4D Printing. Also, within software, it is necessary to develop open access platforms that bring the common user, the main consumer of customizable components, to the 4D universe, also favoring the emergence of creative concepts within DIY (Do-It-Yourself) initiatives. From the standpoint of the layered construction process, it is important to expand the options of AM technologies capable of processing smart materials. In addition, most equipment used for 4D printing is unable to build large parts at once. The development of dedicated machines to produce 4D components on a larger scale, as well as the integration of these systems to experimental platforms, is still something that involves high investments of time and money, which is one of the reasons why most studies in this area are restricted to smaller models [58, 72]. According to Huang et al. [72], the main barriers to the application of 4D Printing in high-tech niches are the lack of production standards and criteria for approval of parts obtained by this new concept, together with the gap between users and 4D techniques, which will only be reduced through training.

The challenges presented above help, in part, to understand the limited number of studies that directly relate the 4D printing issues with civil construction and architecture. Technological novelty, by itself, is a considerable factor that makes research to have, for many years, an exploratory character, of trial and error, limited to the boundaries of the controlled environment and of materials and their relationship with the manufacturing system.

As seen, 4D Printing currently works with a very small group of raw material types, which contrasts with the need for civil construction and architecture to handle materials of high structural level, such as cementitious composites, woods, and metals. In addition to printability issues, the materials mentioned above need to be adapted, in most cases, for printing large-scale structures. Therefore, adjusting the composition

to make them responsive to external stimuli, or selecting a material with such properties can be a difficult task, affected by the instability of the input for processing, by high costs or even by the incompatibility with the current AM tools available.

Although 3D printing of large parts, from a technological point of view, has already presented a significant evolution, building large parts that can be changeable over time is something complex. Imagine a metal bridge with self-assembly feature? Or a set of self-healing concrete walls? These are examples that make us question the effectiveness of 4D designs and materials in providing accurate and safe conditions of energy and sensitivity to lift a large mass and locate and correct cracks over large areas.

The products of civil construction and architecture are elements that directly affect life, so the design of these components for 4D Printing must be reliable to prevent structures from collapsing due to conflicts of environmental stimuli. The Earth is an extremely unstable planet, although ideal for the development of life. Geographic location, seasons, or increasing climate change, temperatures, humidity, UV indexes, incidence of electrical discharges, for example, vary significantly. Many of the factors listed are stimuli for 4D Printings, which would make civil construction projects something non-universal and even in need of seasonal adaptation. However, there is no reason why 4D Printing enthusiasts should not believe in its application in civil construction and architecture. Even in still slow steps, some studies are already evaluating potential materials and concepts for the areas.

Environmental issues will demand that social forces increasingly tighten energy consumption guidelines on buildings. Processes associated with the heating and cooling are responsible for a good part of the pollutant emissions, in addition to a considerable portion of all the energy consumed by the building throughout its life. In this sense, using adaptive facades, that is, the building envelope, is an interesting solution for optimizing the internal conditions of environments as a function of external climatic or luminous characteristics [73–75]. Commercial automated facades are based on sets of devices equipped with electrical systems with actuators and controllers. These elements can be replaced by structures made of responsive materials and with shape memory, within the scope of the 4D design [75].

Composites with a thermoplastic base, with a load of wood dust, have been explored in FFF (Fused Filament Fabrication) 4D Printing to build parts aimed at simulating interactive facades. El-Dabaa and Salem [76], for example, evaluated the use of Poly(lactic acid) (PLA) filaments, with variations in the amount of wood dust (between 20 and 40%), in the production of passive actuator prototypes (on a hinge system) for adaptive façades, which could respond to different humidity levels. In addition to the composite, the work also explores the effects of variation of FFF parameters and geometric/dimensional concepts on the sensitive response of the tested samples.

For the authors, 4D Printing is an asset to be exploited in the construction of wooden actuators to interact with changes in humidity throughout the day and seasons, favoring the production of lightweight shading mechanisms. Furthermore, they point out that the 4D technique allows a more precise control of the movement mechanisms, due to the parametric adjustment of the print, when compared to natural

wood. To allow greater movement speeds and curvature of the parts, it is necessary, according to the paper, to produce filaments with higher concentrations of wood.

Vazquez et al. [77] also studied the application of composite wood filaments in the FFF fabrication of hydroactive architectural films. The authors show that the greater the porosity of printed parts, the faster the objects change shape when exposed to high levels of humidity. Porosity is also an interesting strategy for controlling the transparency of films. In addition, they also emphasize that the variation in deposition angles between layers is responsible for controlling the folds and the final form of activation.

Correa e Menges [78] present in their research a system printed in 4D FFF, responsible for the opening of multiple flaps due to climatic variations, especially relative humidity (R.H.)—Fig. 3. The flaps were designed to perform two types of curvature when stimulated, one along its longest length and one from its edges to the center of the part. When fully closed, the flats allow, due to its two folds, a dome shape for the system.

Correa and Menges' [78] approach involves the use of a hygroscopic material that is responsive for the printing of flaps (wood composites) and a non-responsive material to build the support of the dynamic structures (in this case, the authors used Acrylonitrile Butadiene Styrene—ABS). Figure 3 was included in this chapter because it makes us think of many applications for civil construction and architecture: dynamic facades, interactive windows, pavilion ceilings, systems for controlling air flow or light and, who knows, even a shelter.

Other research is being carried out to evaluate the potential of polymer/wood filaments in the production of 4D architectural components. In addition to evaluating the responsive effect of the material and transformations, the works also focus on



Fig. 3 Multi-kinematic-state climate-responsive aperture time lapse shape change from high R.H.% environment (left) to low R.H. environment (right) [78]. Reprinted from [78] with permission from Professor David Correa

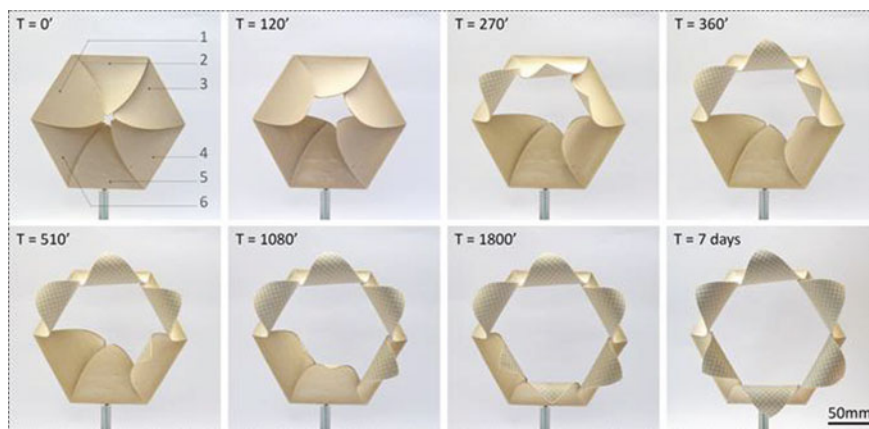


Fig. 4 4D-printed aperture prototype with sequential motion programmed per element shown in six stages. The time-lapse imagens show the six flaps with geometric overlaps taking turns to bend in sequence, resulting in the successful opening of the aperture upon drying in 40% RH [82]. *Reprinted from [82] under CCC Marketplace™ license ID #11515591*

printing components inspired by Kirigami-type structures [79], modular assembly systems in Origami [80] or natural ones, based on movable plant elements [81, 82] (Fig. 4). All the studies mentioned are quite recent, indicating, therefore, a trend in the area and a perspective for a future development of these systems. We must, however, think about what still needs to be done, especially regarding the analysis of the degradation of the polymer base to environmental weather and the development of large-scale parts. This last aspect is highlighted by Vazquez and Gursoy [80], indicating the need for greater print volumes for FFF printers.

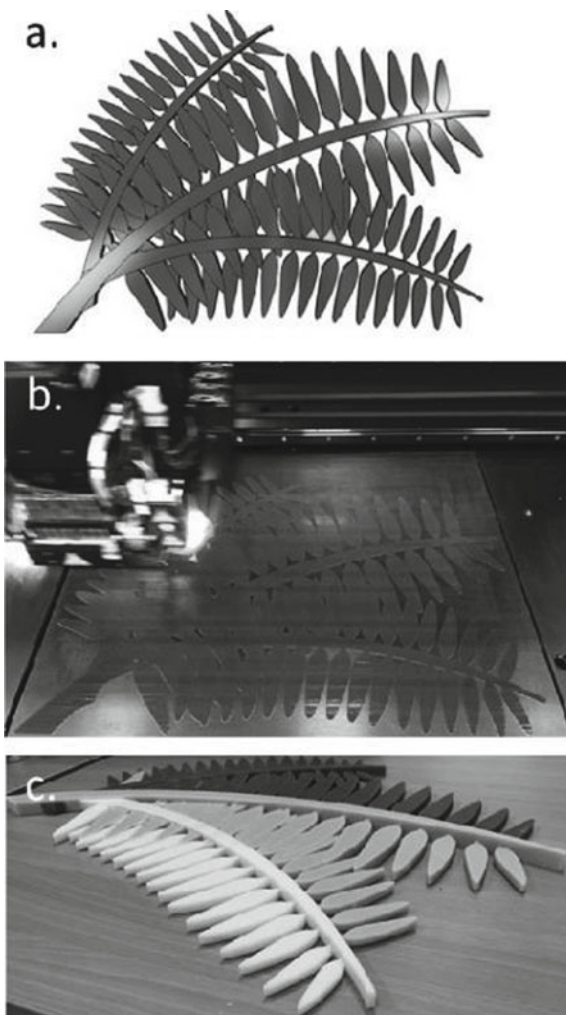
Alternatives to wood composite thermoplastics are presented in the literature for 4D printing of adaptive facade elements, including: SMP filaments for FFF [83–85] and shape memory composites (SMCs) based on SMA fibers grouped in an SMP flexible matrix—the matrix was obtained through the PolyJet™ AM technology, from the combination of Verowhite and Tangoblack (rubber) resins [86]. The materials mentioned, unlike wood composites, activated by moisture, are stimulated by temperature variation.

The observations made by the aforementioned authors are important for the analysis of the architectural applicability of the FFF 4D technology and the materials they use: (i) depending on the geometric complexity of the objects, the need for supports in the 3D Printing step makes the process less productive and eco-friendly incorrect [83]; (ii) SMPs may present instabilities in behavior as a result of manufacturing and operating environments [84]; (iii) in an opening and closing system, the return of the component manufactured with SMP filament to the “open state” is still a challenge, as the feedback force is insufficient and the polymer tends to harden when below its glass transition.

In the study by Yi and Kim [86], with SMCs and the PolyJet™ technique, the following challenges are identified: (i) temperature conditioning to balance viscoelastic and austenitic behavior; (ii) limitations related to the material's mechanical properties and response speed; (iii) resistance to environmental loads (wind, rain, among others); (iv) technical manufacturing problems, i.e., dimensional limitation (size), precision and material composition; and (v) economic feasibility within the existing construction context.

The PolyJet™ technology, mentioned above, was the subject of a study by Teoh et al. [87] on building a 4D smart sunshade (Fig. 5). It works mounted on windows, to execute the closing of the structure when exposed to the heat generated by the solar incidence and its return, its shape and initial position, when cooled. The system is

Fig. 5 3D printed customized sunshade. **a** CAD model; **b** printing process, and **c** printed part [87]. Reprinted from [87] under CCC Marketplace™ license ID #11522301



bioinspired on a tree branch, composed of three branches and numerous leaves. The authors use a multimaterial concept to build prototypes. Photopolymers with different glass transition temperatures are applied, which allows a gradual change of shape with temperature variation. As challenges, they highlight the need to counterbalance the effects of gravity on structure integrity and shape memory effect, improve shape reversibility, response speeds and system durability.

According to Leist [88] 4D printing with hygroscopic polymers may come to be useful for several applications, which include, for example, building self-erecting barriers and shelters for the relief of victims in natural disaster areas or refugees from other situations. According to the author, accommodations can be transferred in flat and compact forms to the installation site and then transformed with the conditions of the application environment.

The idea of emergent structures described by Leist [88] in 2017 was conceptualized and tested in 2019 by Henriques [89]. In her master's thesis, the author presents a shelter model, inspired by origami, manufactured, on a small scale, by the FFF process with SMP filament. Once immersed in hot water, the frame material becomes mobile, allowing the shelter to be folded and compacted for easy transport to the installation site. To return to its initial shape, the folded object must be again exposed to hot water (Fig. 6).

Wagner et al. [90] evaluated the construction of auxetic structures to generate large deformations when exposed to temperature variations. As in the previous study,

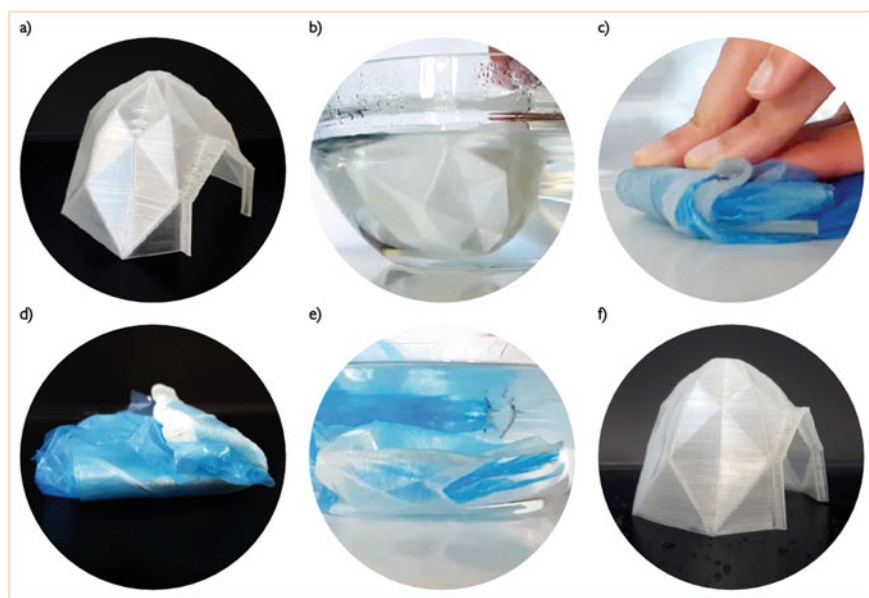


Fig. 6 Printed shelter (a), first hot water immersion (b), folding process (c), compacted structure (d), second hot water immersion (e), and return to the initial shape (f) [89]. Reprinted from [89] with permission from Professor Jorge Lino (Master's thesis supervisor)

the heated aqueous medium was also used to generate stimuli to the system. The active meta-material was obtained through the PolyJet™ technology, with the aid of photopolymeric resin VeroWhite Plus, being able to achieve, throughout the transformations, area changes of up to 200% in the produced parts. The authors indicate that future exploration of this concept may be of interest to civil construction.

Hydrogels also draw attention to many applications in 4D Printing, which include the field of architecture. These raw materials can be used, for example, to improve the performance of glass and windows. Once a thermosensitive hydrogel is inserted between glass sheets, it can act on the opaque behavior of the structure according to the heat generated by the room temperature or by the light incidence, serving, therefore, as thermotropic shading. Another use would be in the making of architectural skeletons, which can be applied as a secondary reinforcement to provide flexible structural support to rigid elements, but also to reduce heat gain and energy consumption in buildings. Like all the materials presented so far, hydrogels are also candidates for to produce adaptive façades [91, 92].

When analyzing the literature using the terms “3D printing” with “self-healing concrete” one can find some interesting initiatives. In the case of self-healing of cementitious structures, two approaches stand out. The first shows the insertion of capsules printed in thermoplastic material, containing in its interior a curing agent (sodium silicate solution and expandable polyurethane), in a cementitious matrix. When the process of formation of cracks in concrete starts, the capsules release the curative element to fill and recover the gaps [93]. The other solution consists in the introduction, in the cementitious mass, of networks of printed connected channels, which may or may not contain curing elements [94]. Interconnected structures, based on biomimetic designs, were printed on PLA to test the pumping [95], storage and distribution [96] of curative materials (sodium silicate) in damaged zones of concrete blocks. All the works mentioned [93, 95, 96] used FFF 3D printing to build the devices and demonstrate that the proposed systems are potential for future investigations in the self-recovery of cementitious structures.

These studies, however, use 3D printing as a tool to build a device capable of introducing the curing agent to concrete structures, which are not necessarily obtained by additive processes. Despite promoting self-recovery, we understand that to approach 4D Printing, the scenario should be of a printable, cement-based material, whose formulation would induce, through the formation of flaws, a transformation of self-regeneration.

Geopolymers composed of alkaline activated metakaolin are intelligent materials with electrical conduction capacity due to the presence of free electrons in their matrix [97]. Vlachakis et al. [97–99] used this property to develop printable pastes to produce sensors for measuring strain and temperature, according to material impedance variation, in concrete structures. These studies, unlike devices for releasing healing agents, bring the formulation and printing of a responsive material, which varies its electrical characteristics over time, with the application of external stimuli: changes in temperature or variations in mechanical loads. The essence of 4D Printing can be seen in these works through the ability of the materials to be “self-sensitive”.

4D Printing still has a long way to go the field of civil construction and architecture, especially regarding important materials such as cementitious composites. The future of 4D technology promises to be revolutionary to produce self-assembling structures for the military industry (shelters, bridges, etc.), self-repairing or self-cleaning structures for difficult-to-access areas, intelligent piping capable of self-healing leaks or changing their diameter according to pressure of water, self-erecting furniture, inflatable decoration objects and much more [47, 57, 68, 100, 101].

4 Final Considerations

After analyzing the literature and movements around 4D printing in construction, it becomes possible to answer the question proposed in the title of this work: 4D printing and construction: reality, future, or science fiction?

We are not going to promote specialist discussions about the definition of science fiction, the fantastic world, among others. Let's think about the vision of someone who reads a book or watches a sci-fi movie. Generally, we are transported to universes with technological advances or concepts that go beyond the potential of the real world at that specific moment. 4D Printing can instigate thoughts, precisely because the human being is used to seeing the world in three dimensions and, therefore, thinking in a fourth dimension can be something complex, or even unreal, for some people. In other words, 4D technology may still be science fiction for the common user, but it is certainly no longer for a good part of the academic/technological community, including researchers in civil construction and architecture.

The confrontation between the real and the fictional around 4D Printing highlights the need to bring this technology closer to DIY movements, as highlighted by Huang et al. [72]. It is plausible to think that the advances seen today in 3D Printing would not have been possible if the open-source movements had not emerged and democratized AM technologies. The non-technical user brought to 3D Printing the ability to think and build without the responsibilities of justifying the "reasons of things" as it is in the academic world.

This enthusiastic vision was able to promote innovations in 3D printers and their peripherals, in the composition of materials, in the computational planning of processes and, of course, in the production of parts that would be useful for home use. "Free science" stirs egos and drives "academic science" to develop applications for 3D Printing above those the average user can do at home. As a result, the industry absorbs this knowledge, promotes investment, and transforms the idea into systems capable of printing, for example, houses and architectural structures with reduced time and costs. The described cycle needs to be inserted in 4D Printing, so that the real needs are identified, and the concept can be understood by society.

We still cannot say that 4D Printing is a reality in civil construction and architecture. For that, it is necessary to scale the embryonic concepts observed in this review, not only in dimensions, but in their reach in the development of products that affect people's well-being and lives. The path to reality, from a technological point of view,

needs to overcome challenges far beyond building high-volume machines, but rather in controlling the heart and brain of 4D Printing: the materials. It is not enough to increase the range of raw materials; it is necessary to stabilize the materials over time. Once you manage to stabilize the processes of transformation, back and forth, and their relationship with external stimuli, the production of machines, software and construction parts will emerge naturally.

4D Printing can be considered the future of civil construction, being something inevitable on a planet that demands clean technologies every day with reduced energy consumption and pollutants. However, defining whether this future is near or not will depend on how open the technology will be to society.

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